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The Development and Application of a Cost per Minute Metric for the Evaluation of Mobile Satellite Systems in a Limited-Growth Voice Communications Market

by

Michael David Violet

B.S., Astronautical Engineering
United States Air Force Academy (1989)

Submitted to the Department of Aeronautics and Astronautics in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Aeronautics and Astronautics
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September, 1995

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The Development and Application of a Cost per Minute Metric for the Evaluation of Mobile Satellite Systems in a Limited-Growth Voice Communications Market

by

Michael David Violet

Submitted to the Department of Aeronautics and Astronautics on August 10, 1995
in partial fulfillment of the requirements
for the Degree of Master of Science in Aeronautics and Astronautics

Abstract

Five companies have recently filed for a license with the Federal Communications Commission to provide handheld mobile communication services in the United States. Three of these companies were awarded licenses in January 1995, while Inmarsat and other non-US companies have announced their intentions to implement systems addressing the same market. The architectures proposed for each of these systems differ substantially in their selection of satellite constellations, multiple access schemes, antenna designs, service availability and network configurations. The effectiveness of each of these design approaches must be measured by how cost effectively they are able to satisfy the expected market.

A market model has been developed to estimate the addressable minutes for the first twelve years of this burgeoning market. Although optimism abounds regarding the size of the expected market, it is quite possible the market may not grow as much or as quickly as anticipated. Systems designed to operate in a large market may be poorly equipped to provide cost effective solutions in a smaller market.

A computer model has been developed to estimate the billable capacity of five mobile satellite services (MSS) designs at different levels of market penetration. To evaluate their effectiveness when operating in a limited market, the billable capacity for each system has been determined at 10% and 31% of the expected market. Life cycle costs have been estimated for each of the systems to address the market over a twelve year period. Costs evaluated include development and operations costs for satellites, launchers, gateways, insurance and PSTN connections. The effectiveness of each system has been evaluated on the basis of the cost per billable minute required to achieve an internal rate of return of 30%.

All systems are shown to provide cost effective services when addressing 31% of the expected market, but costs begin to approach current Inmarsat rates at 10% of the market. With equal market penetration, the system modeled after Globalstar, LEO-48, provides the most cost-effective service, while the LEO-66 system, modeled after Iridium, requires the highest cost per minute. These results are shown to be very dependent on the level of market penetration allowed, and indicate that other factors such as marketing strategy, quality of service and access to the global marketplace will dominate.

Thesis Supervisor: Dr. Daniel Edgar Hastings
Title: Associate Department Head for Research
Professor of Aeronautics an d Astronautics

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Cary Gumbert, my fellow masters student and friend, deserves credit for much of the work in this thesis. In the past year, we have worked together on this project and learned a lot about mobile satellite systems, and systems engineering along the way. We initially attempted to split the project up into discrete responsibilities, with Cary concentrating on communications, capacity and cost, and myself concentrating on the orbital geometry, programming the *Vircap* model, and other aspects of cost. We quickly learned that such a complex systems study required us both to become intimately familiar with all of the details. In every way, this thesis represents the combined work of both partners. I highly recommend his thesis to provide additional insights into mobile satellite systems.

This project never would have begun without the support of GM Hughes Electronics and Michael Armstrong who sponsored the MIT study. Dr. Gerald Dutcher at Hughes also provided great assistance as the technical monitor for the project. I hope that the project and this thesis are to their liking.

Special thanks goes out to both the United States Air Force for allowing an Air Force officer the opportunity to further his education, and to Maj. Jim Hogan and the folks at AFIT/CIS at Wright Patterson for supporting me this past year.

A phenomenal number of people provided assistance without which this thesis could never been accomplished. The guest lecturers who came to speak to Bob Lovell's 16.89 Space Systems Engineering class provided insights into the mobile satellite industry that would have taken a lifetime to accumulate - and probably did. Specifically, I would like to express my appreciation to Olof Lundberg from Inmarsat, Dr. Elizabeth Young from Comsat, Jan King from Orbital Sciences Corporation, Dr. Bob Francois, Arthur Curly, Paul Babbitt, and Dr. Jack Schust from Raytheon, Walter Morgan from Communications of Clarksburg, Ed Jurkiewicz from Comsat Consulting Group, Jack Juraco from Hughes Space and Communications, Roger Rusch from TRW, and Dr. Andrew Viterbi from Qualcomm for taking the time to come to MIT and help out the class. The 16.89 class itself also deserves a great deal of credit for this thesis as it grew directly out of our class project. I thank you all for the suggestions, hard-work, insight, and patience that you showed Cary and I throughout the semester. Special thanks to Amir R. Amir, Stacy Cowap, Capt. Ross McNutt, Bhavesh Patel, Graeme Shaw, and Susanne Schroll for their friendship and assistance with the thesis.

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While I'm rolling, I would like to thank the Astronautical Engineering Department of the United States Air Force Academy for providing me with most of the engineering knowledge I have today. Specifically to Lt. Col. Daryl Boden, my advisor, and Maj. Riggs.

Lastly, and most importantly, I would like to thank my wife Jean, my parents, and the rest of my family for their love, support and understanding.

By Perseverence the Snail Reached the Ark.

-Unknown

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1. Introduction

Terrestrial cellular communications has experienced a period of phenomenal growth in the past ten years. The number of cellular phones in use throughout the world increased from 7.8 million in April 1990 to over 15.8 million in May 1992 to 33.9 million in January 1994 [Ananasso, 1994; Impoco, 1993; Herring, 1994]. According to Craig McGaw, chairman of McGaw Cellular Communications, there were over 11 million cellular customers in the United States by mid-1993, and they were being added at a rate of 9700 per day [Impoco, 1993]! With at most a five percent market penetration rate in the United States and most of Europe [Herring, 1994], it is clear that the current trend towards mobile communications has room to grow.

Motorola's marketing research has found that around 40 percent of the "world's workforce is nomadic -- on the road, off-site, in the air, and overseas. In America alone, some 40 million employees now work away from the office for lengthy periods" [Haynes, 1993]. However, "it is projected that cellular, and other forms of terrestrial mobile communications such as the burgeoning personal communication systems (PCS) market, will cover over 50 percent of the world's population but only 15 percent of the land area by the end of the century" [Herring, 1994]. Due to the increasing demand for mobile communications services, there has been a push in the United States and Europe to expand the cellular network to fill these gaps in cellular coverage.

The current trend in communications is towards high capacity, digital, cellular networks, which in turn require a large density of cellular towers [Ananasso, 1994]. Satellite networks could provide complementary service in those areas where the expense of developing a cellular infrastructure is prohibitive [Michel, 1994]. In developed areas of the world, such as the United States and Europe, mobile satellite services are planned to complement existing fixed and cellular services. However in most of the underdeveloped and developing countries of the world (such as China and the former Soviet Union), extensive telecommunication services are unavailable. It will be some time before the infrastructure required to expand the Public Switched Telephone Network (PSTN) and cellular services can be extended to these regions of the world. In the last few years, many companies have proposed filling the gaps in cellular service and extending the mobile communications network across the globe by utilizing satellite constellations.

1.1 Mobile Satellite Systems

Five companies have recently filed for a license with the Federal Communications Commission to provide handheld mobile communication services in the United States: Motorola, Loral/Qualcomm, TRW, Mobile Communications Holdings, Inc., and Constellation Communications. Three of these companies, Motorola, Loral/Qualcomm and TRW were awarded licenses in January 1995, while INMARSAT and several other non-US companies have announced their intentions to implement systems addressing the same market.

The basic idea of these systems is to provide mobile communications to small, cellular-sized handheld terminals throughout the world by setting up a satellite-based communications network. In essence, these satellites will operate as extremely tall cellular towers, only in this case the towers will be moving. The satellite systems that have been proposed differ substantially in their selection of satellite altitudes and communications designs, but in the end they all mean to

provide service to mobile customers anytime, anyplace and anywhere. Figure 1-1 illustrates the idea.

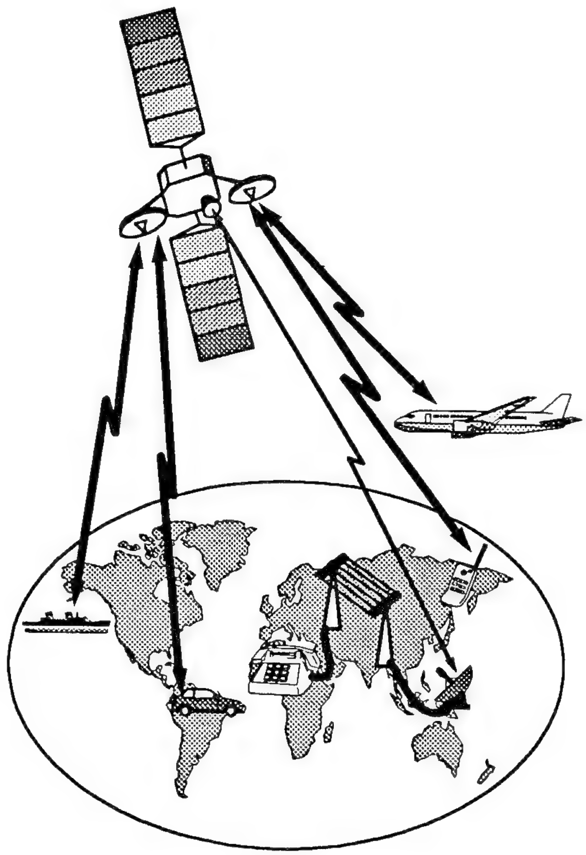

Figure 1-1 Mobile Satellite Communications.

Although many of the characteristics of the proposed systems are different, fundamentally the basic process of making a phone call will be the same. For example, a traveling salesperson who wants to check in with the home office will attempt to place a call through his satellite phone. Since all of the proposed systems are providing a service that is complementary to the cellular networks, he will probably own a dual-mode phone - one that is capable of operating through both the user's home cellular network, and the satellite system. If possible, the phone will place the call through the local cellular network. However, if the salesperson is outside of a cellular coverage region, or in an area

providing an incompatible service, the call will be connected to the nearest available satellite that is in view to the user. Most of the proposed satellite systems will then relay the call directly back to a gateway antenna on the ground so that it can be connected to the public switched telephone network (PSTN) which would then connect with the office. If instead the target of the salesperson's call is another mobile user, the call will be routed through the PSTN to a gateway near the other party, where the call will be routed through another satellite and transmitted to the other user. One of the systems, however, will have the additional capability of routing the call through the satellite system without ever having to connect to the ground unless it needs to do so. The Iridium system will be able to connect calls in this manner by using satellite crosslinks - communication links provided between the satellites themselves.

Although the basic purpose of them is the same, satellite systems have been proposed to operate in three basic orbital classes: low Earth orbit (LEO), medium Earth orbit (MEO), and geosynchronous orbit (GEO). The vast majority of the world's communications to date have been provided from GEO. Due to its unique orbital distance, the rotation rate of a GEO satellite matches the Earth's rotation rate so that it remains fixed over the same point on the Earth's surface. Despite the obvious benefits of a fixed satellite, many of the proposals call for systems placed in orbits much closer to the Earth due to other perceived benefits. The debate between which type of system will provide better service involves many different aspects of the system designs, and the answers do not always seem clear. However one thing is certainly true - provided each of the proposed architectures can provide voice service that is considered of acceptable quality to the end user, the effectiveness of each of these design approaches will be measured by how cost effectively they are able to satisfy the expected market.

"Current forecasts suggest that the total worldwide mobile satellite market will be worth as much as $17 billion by the year 2003, compared with about a billion

dollars today" [Herring, 1994]. With such large potential revenues, the competition between different systems has become fierce in the last few years. In order to evaluate these systems, a market model has been developed to estimate the expected traffic level in minutes per year (addressable minutes) for the first 12 years of this burgeoning market. Although optimism abounds regarding the size of the expected market, it is quite possible the market may not grow as much or as quickly as anticipated. Systems designed to operate in a large market may be poorly equipped to provide cost effective solutions in a smaller market.

1.2 Thesis Objective

Traditionally, fixed service communications have been performed by satellites in geostationary orbits using fixed, wideband transponders. The capacity of these systems was marketed on the basis of leasing these transponders. A common metric used to evaluate geostationary communications satellites was the on-orbit cost per transponder year [Lovell, 1983]. This metric provided a direct relationship between system cost and performance, and provided a meaningful way to evaluate the cost effectiveness of competing satellite designs. Although mobile communication systems should be evaluated by a similar metric, the satellite capacity will be marketed on the basis of a single voice circuit. Accordingly, the metric to use when evaluating mobile communication satellite systems should be the cost per billable minute.

The purpose of this study is to address the LEO vs. GEO debate in a rigorous way, by evaluating how well five different mobile satellite system architectures are able to satisfy a limited-growth voice communications market. This study will be conducted within the framework of the systems engineering process and the effectiveness of each system will be evaluated based on the cost per billable minute metric.

1.3 Overview of Thesis

Figure 1-2 provides an overview of the structure of the thesis. After this introduction, chapter 2 will begin by providing an overview of the history of satellite communications and mobile satellite communications in particular. This chapter will introduce the reader to the trends that have made satellite communications through handheld terminals possible, and provide a summary of the characteristics of the major systems that have been proposed. The chapter will close with a summary of the major issues in the LEO vs. MEO vs. GEO debate, and an overview of a few major evaluations that have been conducted in the literature.

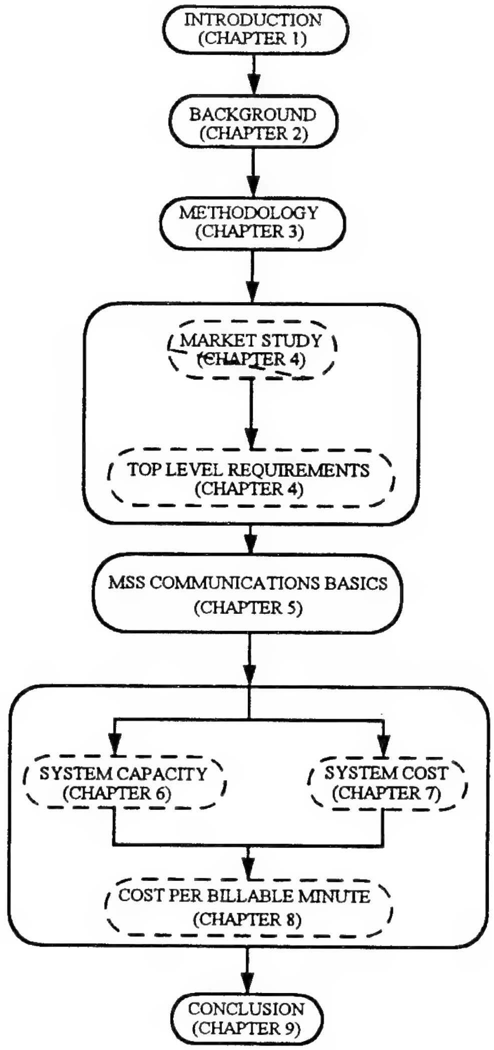

Figure 1-2 Overview of the Thesis

Chapter 3 will describe the methodology utilized to evaluate the various systems and fit it into the framework of both the capital budgeting and systems engineering processes.

The first step of the systems evaluation, the determination of the expected market, will be provided in Chapter 4. This chapter will summarize the results of a market study conducted by KPMG, Peat Marwick's Advanced Technologies Group. The results of this study will be extrapolated to determine the size of the addressable market throughout the first 12 years of the handheld mobile satellite

services market. The chapter will close by summarizing the top level systems requirements that were derived from the customer preferences survey conducted by KPMG.

Chapter 5 will provide the reader with an introduction to the basics of mobile satellite communications. The discussion will be concerned primarily with a derivation of the fundamental link equation and a summary of its various parameters.

The system capacity model will be described in detail in chapter 6. The description of the model will begin with a brief overview and then derive expressions that describe the constraints that limit the billable capacity of the system. The final part of the chapter will describe the detailed flow of the simulation.

Chapter 7 will describe the methodology of the cost analysis. The chapter will discuss the various models used to derive satellite, launch vehicle, insurance, gateway, operations and public switched telephone circuit (PSTN) connection costs over the 12 year lifetime of each system, providing cost results at each stage of the estimating process. The chapter will close with the summary of the total first and second generation costs for each system at 10% and 31% market penetration levels.

Chapter 8 will integrate the cost results of chapter 7 with the capacity results of chapter 6 by determining the cost per minute required for each system to achieve a 30% internal rate of return (IRR).

The study results will be concluded in chapter 9. The chapter will provide a brief summary of some other issues that could play a major factor in the mobile satellite services competition, and present the final conclusions.

The conclusions will be followed by two appendices. Appendix A lists the traffic model maps derived for the years 2000 to 2012 and Appendix B lists the control files used to model each of the evaluated system architectures.

2. Background

2.1 Historical Background

The first step towards providing communications from space-based platforms began in 1946, when the Army first achieved radar contact with the moon [Martin, 1991]. By the late 1950s, the U.S. Navy became the first user of communications satellites when they established an operational, low datarate communications link between Washington, D.C. and Hawaii by using the moon as a passive reflector [Pritchard, 1993]. Early man-made satellites, such as SCORE (Signal Communications by Orbiting Receiving Equipment), launched in late 1958, and the Project ECHO satellites, launched in 1960 and 1964, represented early efforts to test the concept of satellite-based communications. During its thirteen day lifetime, SCORE operated as the first store-and-forward satellite by recording voice and telegraph messages, and later retransmitting them to the ground. The ECHO satellites operated as simple repeaters, in that they merely reflected incident RF radiation back to the ground. Although these passive reflectors allowed robust communications with wide bandwidths and multiple access capabilities, they were soon outpaced by active repeaters - satellites that receive, process, and then retransmit incident signals.

The first step towards commercial communications began when Telstar 1, an active repeater designed and built by Bell Telephone Laboratories, was launched

by NASA into a medium altitude, elliptical orbit in 1962. The Telstar series (Telstar 2 followed in 1963) was soon followed by the first attempt at active communications from geosynchronous orbit (GEO) - an orbit with an altitude of 22,282 miles, attaining an orbital period equal to the period of the Earth's rotation. Although the Syncom 1 satellite was lost in February 1963 during injection into its final orbit, it was soon followed in July by the launch of Syncom 2, the first geosynchronous communications satellite, and the subsequent launch of Syncom 3, the first geostationary communications satellite, in August 1964. Geostationary satellites are also located in geosynchronous orbit, although their orbital plane lies on the equatorial plane. This unique orbit is referred to as geostationary since a satellite in that orbit will appear to hang motionless over a spot on the equator.

Commercial satellite communications stepped into high gear in August 1962, when President Kennedy signed the Communications Satellite Act of 1962, which established the Communications Satellite Corporation (Comsat). Comsat was established in order to create "a commercial satellite telecommunications system which, in cooperation with other nations, could be expanded to a global system that would make efficient and economic use of the radio spectrum while giving attention to the needs of both developed and lesser developed nations" [Field, 1994]. Comsat was incorporated in February 1963, preceding the establishment of a "quasi-governmental multinational organization," the International Telecommunications Satellite Organization (Intelsat) in July 1964.

Intelsat launched the world's first commercial communications satellite, *Early Bird* (Intelsat I), into geosynchronous orbit in April 1965. The demand for satellite-based telecommunications services has grown tremendously in the years that followed the launch of this single satellite. Table 2-1 bears testimony to this expansion, showing the increasing communications capability (measured in two-way telephone circuits) of successive generations of Intelsat satellites

[Lovell, 1983; Martin, 1991]. Recall that a circuit refers to a two-way (full-duplex) communications link between two Earth terminals whereas a channel refers to a one-way link [Pritchard, 1993].

Table 2-1 Telephone Circuit Capacity of Successive Generations of Intelsat Satellites

Intelsat Generation	Year of First Launch	Capacity (Telephone Circuits)
Intelsat I	1965	240
Intelsat II	1966	240
Intelsat III	1968	1200
Intelsat IV	1971	4000
Intelsat IVA	1975	6000
Intelsat V	1980	12000
Intelsat VA	1985	15000
Intelsat VI	1989	33000
Intelsat K	1992	65000
Intelsat VII	1994	90000
Intelsat VIIA	1995	112500
Intelsat VIII	1996	112500

Along with the tremendous growth in international telecommunications, other satellite-based communications systems began to be considered for provision of communications to selected regions of the Earth in the early 1970s, due to a drop in the cost of satellite communications [Pritchard, 1993]. Telesat Canada's Anik A1 satellite, launched in 1972, became the world's first domestic communications satellite [Martin, 1978]. Communications companies in the United States leased capacity on both Anik A1 and Anik A2, until the first Domsats (domestic satellites) in the U.S., the Westar series, were developed and launched by Western Union in 1974.

Before moving ahead with the history of mobile communications, it is useful to provide an overview of the frequency bands used for communications. Frequencies are usually specified in terms of hertz (one cycle per second), or alternatively by their wavelength. A method of classifying bands of frequencies

for use in communications has developed by segmenting the frequencies in factors of ten. Table 2-2 displays the standard frequency designations.

Table 2-2 Standard Frequency Designations [Chetty, 1988].

BAND	NAME	FREQUENCY RANGE	(units)
ELF	Extremely low frequency	30-300	Hz
VF	Voice frequency	300-3000	Hz
VLF	Very low frequency	3-30	kHz
LF	Low frequency	30-300	kHz
MF	Medium frequency	300-3000	kHz
HF	High frequency	3-30	MHz
VHF	Very high frequency	30-300	MHz
UHF	Ultra high frequency	300-3000	MHz
SHF	Super high frequency	3-30	GHz
EHF	Extremely high frequency	30-300	GHz
VEHF	Very extremely high frequency	300-3000	GHz

An alternative method of classifying frequency bands was developed during World War II. The higher frequency bands (from 1 to 50 GHz) were segmented into narrower bands and "assigned letter designations for purposes of military security... To enhance security, the designations were deliberately put out of alphabetical sequence" [Stimson, 1983]. Table 2-3 displays some of these designations.

Table 2-3 Letter Designations for Frequency Bands [Gordan, 1993].

LETTER	APPROXIMATE FREQUENCY RANGE	TYPICAL USAGE
L	1.5-1.6 GHz	Mobile-Satellite Service (MSS)
S	2.0-2.7 GHz	Broadcasting Satellite Service (BSS)
C	3.7-7.25 GHz	Fixed-Satellite Service (FSS)
X	7.25-8.4 GHz	Government Satellites
KU	10.7-18 GHz	Fixed-Satellite Service (FSS)
KA	18-31 GHz	Fixed-Satellite Service (FSS)
Q	44 GHz	Government Satellites

Most of the history discussed previously relates to satellite communications between fixed ground station sites; however communications between mobile users have been developing for nearly as long. During 1965 and 1966, the Department of Defense (DOD) conducted communications tests between fixed ground stations, one ship terminal, and aircraft terminals, utilizing the two Syncom satellites. In the early 1960s, the DOD began developing satellites for

strategic communications as part of the Initial Defense Communication Satellite Program (IDCSP). The satellites, launched from 1966 through 1968, were designed to operate with large fixed antennas, transportable ground stations or large shipborne equipment [Martin, 1991].

Progress towards more mobile communications began with the Lincoln Experimental Satellite (LES) series developed by MIT's Lincoln Laboratory [Ward, 1989]. The LES satellites investigated various aspects of tactical communications and demonstrated that UHF communications using simple, low gain antennas were possible. Research from the LES satellite program led to the development of an operational satellite for tactical communications - the Hughes TACSAT satellite. TACSAT, launched in February 1969, was tested with a variety of terminals, including both fixed and mobile ground stations, aircraft and ships. Although both LES-6 and TACSAT were extensively used for tactical communications by the Navy, they provided limited capability as they were essentially developed for research purposes.

The Navy began developing the FleetSatCom satellites to provide full operational capabilities for fixed and mobile terminals on surface ships, submarines and aircraft, as well as on the ground. The first FleetSatCom satellites were not expected to be deployed until 1977, but since TACSAT failed in 1972, and LES-6 was deteriorating, the Navy contracted with Comsat to develop a satellite to fill the expected gap in tactical communications capability. The Gapsat satellite, built by Hughes Aircraft Co., was a derivative of the Anik satellite design. The Gapsat system included 3 geosynchronous satellites to provide global tactical communications to the U.S. Navy. Because military requirements did not require full use of the satellites, Comsat added additional C-Band communications equipment to provide commercial ship to shore communications, and the first commercial mobile satellite communications system was born.

The first Gapsat satellite was launched in February of 1976 and began providing services to the U.S. Navy in the Atlantic Ocean. The remaining two satellites were launched later in 1976, providing service over the Pacific and Indian oceans. Commercial service through this system, commonly known as Marisat (Maritime Satellite), was initiated in mid-1976. True global communications services finally became available to commercial mobile users in 1978, when the Japanese communications carrier, Kokusai Denshin Denwa Co., built the third and final Earth station to complete the global network [Martin, 1991].

The maritime communication services provided by the Marisat system led to the formation, in 1979, of the International Maritime Satellite Organization (Inmarsat) - an international organization similar to Intelsat, founded to improve worldwide maritime communications for peaceful purposes. Inmarsat began commercial voice and data services to maritime users in 1982 by leasing C- and L-band transponders on the Marisat satellites from Comsat [Bulloch, 1993], and quickly upgraded the system in 1983 by adding two Marecs (*Mar*itime *E*uropean *C*ommunications *S*atellite) satellites, and leasing additional capacity on some of the Intelsat V satellites. Demand for Inmarsat's maritime communications services has grown dramatically over the last fifteen years, so prompting Inmarsat to launch a second generation of Inmarsat II satellites, starting in 1990, to meet this increased demand. The current system provides maritime communications services to a wide range of terminals using the Intelsat II system, and utilizing some of the Marecs and Intelsat satellites as backup [D'Ambrosio]. Inmarsat is currently building a third generation of satellites to provide a greater range of services to mobile users.

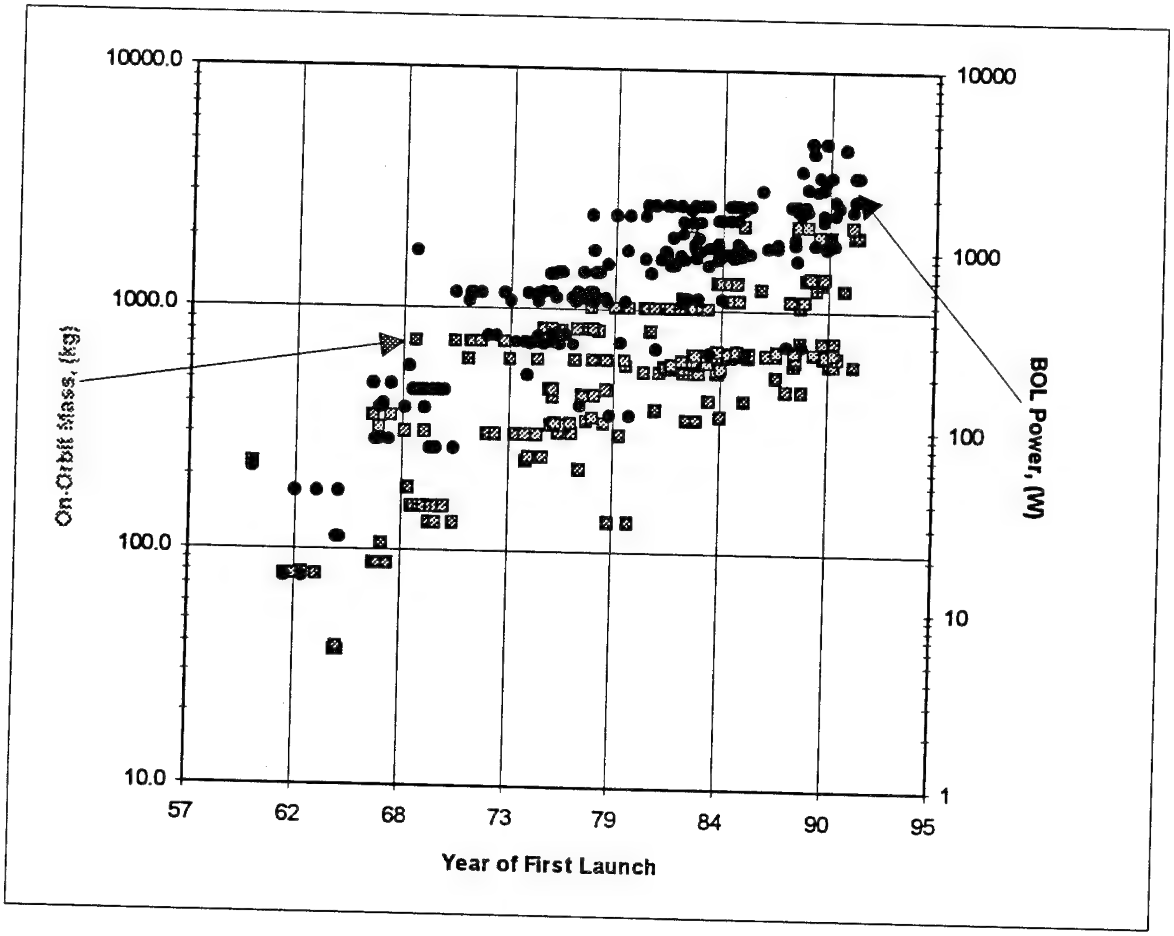

Figure 2-1 **Communications Satellite Mass and Power Trends [Martin, 1991].**

Over the years, communications satellites have been getting larger - both in mass and power. Figure 2-1, displaying on-orbit mass and beginning-of-life (BOL) power for commercial (international and domestic) and military communications satellites, bears testimony to this trend. Since communications capability is closely related to spacecraft mass and power [Lovell, 1983], this growth has largely followed the fast growing demand for satellite communications around the world [Koelle, 1983]. Figure 2-2 shows the relationship between full-duplex (i.e. two-way) telephone circuit capacity and on-orbit satellite mass for the INTELSAT series [Lovell, 1983].

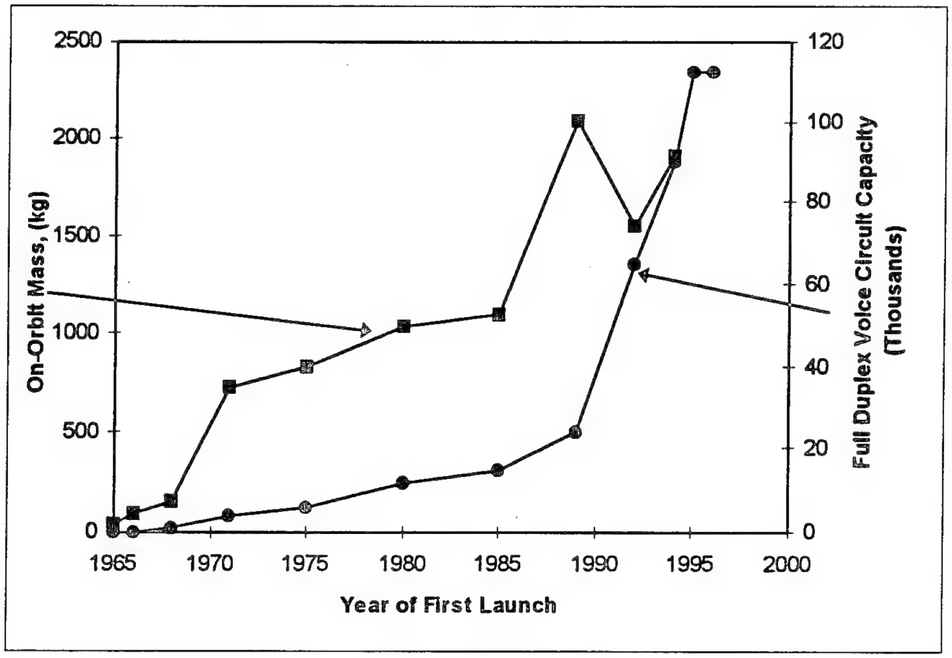

Figure 2-2 Mass and Capacity Growth Trends in the Intelsat System.

As launcher capabilities increased, they allowed for larger satellites. Larger satellites enabled higher power, larger antennas, and consequently more gain since the gain, or focusing ability, of an antenna is related to its diameter. This trend enabled a corresponding reduction in Earth-terminal size, as shown in Figure 2-3 [Atkins, 1995].

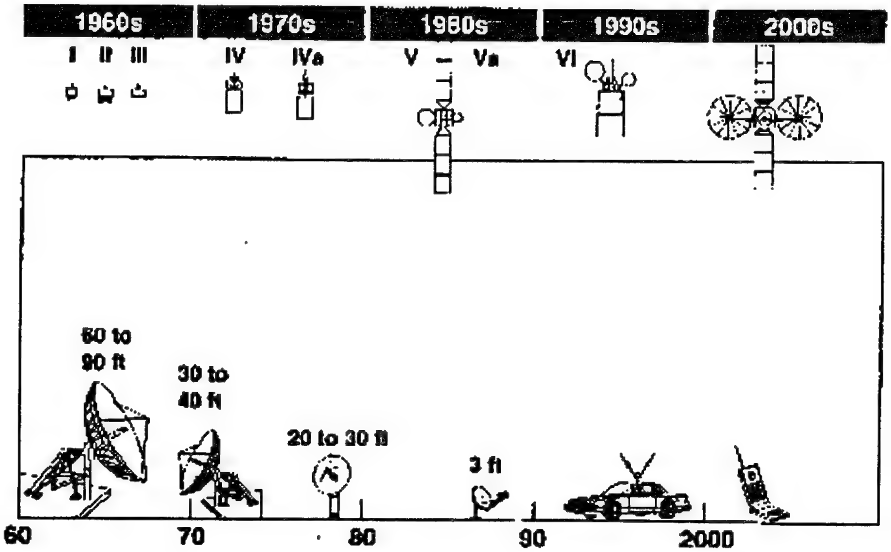

Figure 2-3 Commercial Space Communications Trends: Satellites & Terminals [Atkins, 1995].

This illustration depicts the decreasing size of Earth terminals on the bottom correlated with the increasing size of the Intelsat satellites. The early satellites required large ground antennas from 60 to 90 feet in diameter. As satellite capabilities have grown, Earth station diameters have shrunk such that today's higher powered satellites allow television transmission to small 18 inch receiving antennas. Nowhere does this shrinking terminal trend appear clearer than in the growth of Inmarsat services.

Inmarsat has been providing mobile satellite services for the last 15 years, addressing a "45,000-strong global subscriber base that's growing at a rate which is about to accelerate through one thousand a month" [Thacker, 1995]. This subscriber base has been supplied with a range of services "through ever cheaper and smaller services" [Herring, 1995]. Currently, a wide variety of different services are provided using four main types of terminals.

Inmarsat-A: Inmarsat-A terminals have provided analogue telephone, fax and data services at up to 9,600 bits per second since the late 70s [Singh]. These services are primarily used on large oil tankers, container ships, and bulk cargo

ships from 1.2 m diameter antennas weighing 91 kg, although smaller suitcase-sized transportable terminals weighing as low as 21 kg are also in use on smaller ships and on land [Jurkiewicz, 1995]. Inmarsat-A terminals range in price from $25,000 to $35,000 per unit, and cost from eight to ten dollars a minute during peak service times [Thacker, 1995].

Inmarsat-B: The digital equivalent to Inmarsat-A, Inmarsat-B has offered similar services and terminal sizes since early 1994 at lower peak-usage rates of five to six dollars a minute [Thacker, 1995]. The Inmarsat-B terminals range in price from $35,000 to $50,000 per unit [Thacker, 1995].

Inmarsat-C: Store-and-forward messaging services, whereby fax and e-mail-type messages are sent up to a satellite, stored on board, and then retransmitted back to the ground at a later time, have been offered from Inmarsat-C terminals since 1991. These briefcase-sized terminals (approximately 5 kg) [Thacker, 1995] utilize antennas that are less than a foot in diameter [Jurkiewicz, 1995], and are used primarily on small ships, trucks and aircraft. The terminals, which do not support voice services, range in price from $7,000 to $12,000 per unit, and cost from $1 to $1.5 dollars per kilobit of data [Ananasso,1995].

Inmarsat-M: Starting in 1992, telephone, fax and data services have been offered from smaller-sized briefcase terminals. The one-foot diameter antennas weigh from 29 to 39 kg, and are accessed through 10 kg terminals [Jurkiewicz, 1995]. Inmarsat-M terminals currently cost from $13,500 to $20,000 per unit [de Selding, 1994] (expected to soon cost as little as $10,000 per unit), and provide peak services from five to six dollars a minute [Thacker, 1995].

Mini-M: Inmarsat will introduce new laptop-sized versions of the Inmarsat-M services as early as 1997. The terminals are expected to weigh about 3 kilograms, and be less than half the cost of the Inmarsat-M terminals [de Selding,

1994]. Usage costs are expected to range from three to five dollars a minute [de Selding, 1994]. A small, lightweight antenna for the top of a motor vehicle will be offered as well.

These terminals have clearly decreased significantly in size from the 91 kg Inmarsat-A terminals down to 3 kg Mini-M terminals soon to be released. The terminals, however, are still shrinking. The advancement of technology has made it possible to provide telephone services to small terminals about the size of a cellular phone. In the last few years, a number of companies have proposed providing global voice services to handheld terminals by the turn of the century. Since the provision of these new services will require new frequency allocations, it is useful to look at the regulatory history.

2.2 Regulatory Background

Since Inmarsat's primary service areas were for maritime and aeronautical mobile systems, there were no frequency allocations for land mobile satellite services in the late 1970's. In 1975, NASA began the process of convincing the International Telecommunications Union (ITU) to allocate frequency spectrum in the 800 MHz, and 1500 to 1600 MHz range for land mobile satellite services [Ciesluk, 1992]. The ITU is a specialized agency of the United Nations, chartered in 1932 to develop and regulate international communications in order to promote international cooperation in the efficient use of the radio spectrum [Schrogl, 1994].

Regional and global frequency allocations, located in the Table of Frequency Allocations in the ITU Radio Regulations, are revised during periodic Regional Administrative Radio Conferences (RARC) and World Administrative Radio Conferences (WARC). During the Space WARC in 1979, the ITU allocated 800 MHz for land mobile satellite services. After NASA petitioned the Federal Communications Commission (FCC) in 1982 to provide a domestic allocation for

land mobile services to experiment in the UHF band, two companies, Mobilesat and Skylink, applied to the FCC for licenses to provide land mobile satellite services in the U.S. By 1985, the FCC had allocated frequencies in the L-band for domestic land mobile satellite systems. The L-band frequencies were allocated in the U.S., despite the lack of international frequency allocations, due to potential interference problems in the UHF band.

Following the domestic allocation in the L-Band, twelve companies applied for licenses to provide land mobile satellite services in April 1985 [Satellite News, 1992]. In order to avoid competitive hearings, the FCC advised the twelve individual companies to form a consortium in 1987. In the same year, the ITU extended the L-band allocations internationally during WARC-87. In addition, the ITU also set aside approximately 16 MHz of spectrum in both the 1.6 and 2.4 GHz bands for radio determination satellite services (RDSS) - position location services provided from space-based platforms.

In 1988, eight of the original twelve companies that applied for licenses with the FCC (Hughes Communications Mobile Satellite Services, McCaw Space Technologies, Transit Communications, Mtel Space Technologies, Mobile Satellite Co., North American Mobile Satellite, Satellite Mobile Telephone and Skylink) formed the American Mobile Satellite Consortium (AMSC) and applied to the FCC for authority to provide voice service for domestic mobile satellite services in the L-Band utilizing three geostationary satellites. The FCC granted a license to AMSC for their MSAT proposal in the following year. Although MSAT represented the first application to provide mobile voice services using a satellite-based system, its design does not provide service to handheld terminals. Instead, the MSAT system would provide voice and data services to small, low gain terminals mounted on automobiles or other vehicles.

In February 1990, Orbital Sciences Corporation (OSC) proposed the first private satellite system, Orbcomm, designed to provide global, handheld communications services directly to the end user. In their application to the Federal Communications Commission, OSC proposed to provide low data rate, two-way communications to small handheld digital pagers, through a network of 26 small satellites in low Earth orbit. The OSC proposal was quickly followed by applications from other companies proposing similar LEO-based, global paging services with names such as Starsys, Vita and Leosat. These low data rate services have been since dubbed "Little LEO" systems.

In June of 1990, Motorola announced the first plans to provide global, two-way voice communications to cellular phone-like, handheld terminals through a network of 77 LEO satellites. In November 1990, Ellipsat (now Mobile Communications Holdings, Inc. (MCHI)) filed the first application with the FCC to provide global, mobile voice services in the United States using small, low-Earth orbit satellites. Ellipsat proposed to utilize the 1.6/2.4 frequency bands set aside by the ITU for RDSS services, and therefore planned to provide position location services in addition to voice and data services. The Ellipsat application was quickly followed by an application in December of 1990 from Motorola to provide similar services in the same bands for its 77 satellite Iridium system.

After receiving the two "Big LEO" applications, the FCC set a cutoff date in June of 1991 to receive comments and new applications for global, satellite-based mobile voice services. Loral, TRW and Constellation Communications each filed applications to provide similar services in the same bands by the cutoff deadline. In October of 1991, the FCC submitted early copies of the five proposals for Big LEO services to a division of the ITU in order to facilitate international acceptance for these services, and to prepare for WARC-92, which was set up to specifically address mobile satellite services issues.

During WARC-92, the ITU formally reallocated the 1.6/2.4 GHz RDSS bands for the Big LEO systems, and set aside additional spectrum for Little LEO services. The *primary* allocation of the 1.6 GHz band was assigned for the Earth-to-space link, while the 2.4 GHz band was set aside for the space-to-Earth link. The ITU assigned a *secondary* allocation in the 1.6 GHz band for space-to-Earth links, since Motorola planned to use this band to communicate in both directions. In addition to allocating the RDSS bands to the mobile satellite services on a worldwide, *primary* basis, they also set aside "230 MHz at S-band from 1885-2025 MHz (140 MHz) and 2110-2200 MHz (90 MHz)...", and an additional 60 MHz of spectrum, "...30 MHz (1980-2010 MHz) + 30 MHz (2170-2200 MHz) were provided to MSS for use globally on a *secondary basis* after 2005 (1996 in USA)" [Ananasso, 1995].

Over the four years since MCHI filed the first application, the FCC has conducted "numerous rulemaking proceedings leading up to the adoption of spectrum allocations and licensing rules for the new MSS above 1 GHz service." Since the 16 MHz available in each of the 1.6 and 2.4 GHz bands represented very little spectrum for up to six systems to use simultaneously, very careful attention was given to how the spectrum could be shared amongst multiple systems. As early as 1993, the FCC attempted to convince the proposed systems to agree on a scheme to share the spectrum; although the parties agreed to minimize interference between their systems, they were unable to agree on a sharing approach [Ciesluk, 1992]. The major impediment to an agreement involved the multiple access approach the different systems were planning to employ.

Multiple access schemes are different methods that allow multiple signals to be transmitted in the same spectrum (an overview of the main methods that are currently used will be provided in chapter 4). Motorola designed Iridium to allow multiple access to the spectrum by assigning each user a specific time slice

in a frequency band. This type of system, called time division multiple access (TDMA), operates much like a teacher who separately selects individual students who raise their hands to speak. By quickly collecting small bursts of transmission from each user at separate times, the individual signals do not interfere with each other, and the system is able to put each signal back together on the other end.

The other technique, planned for all of the other systems, assigns each individual user a separate code so that the receiver at the other end can distinguish between the different users, and transmits the signal over a much wider bandwidth to reduce the interference between the users. This method is commonly called code division multiple access (CDMA), and one way of understanding how it works is to imagine a cocktail party. Although lots of people are speaking at the same time, and the room can get very noisy, it is still possible to distinguish a single voice from all of the others, if you know to whom you are listening [Viterbi, 1995]. In the same way, CDMA assigns individual codes to each user so that the receiver at the other end knows to whom it is listening. Although each additional user increases the noise floor, and slightly degrades the capabilities of the system, the larger bandwidth occupied by each signal compensates this noise. TDMA therefore tries to avoid interference between users by transmitting each signal at a unique time and frequency, while CDMA systems transmit each signal simultaneously over the same spectrum and reduce the effective noise by using unique codes and spreading the signals over a wider bandwidth.

The main problem between these two approaches is that they cannot easily coexist in the same spectrum. CDMA requires that signals be transmitted over a wide bandwidth so that the power received within a segment of the band is low, while TDMA transmits high-powered bursts of data in small segments of bandwidth that it alone must occupy. As could be expected, two frequency sharing plans were proposed to the FCC by the systems. Motorola suggested a

band segmentation approach by which the 16 MHz of L-Band spectrum (since they did not plan to use the S-Band at all, they did not propose a sharing scheme) is split in two equal segments - one for TDMA systems, and the other for CDMA systems [IWG1, 1993]. Of course since they were the only TDMA system, it would allow Iridium sole use of 8.25 MHz of spectrum. The other method, proposed by the other systems, was called *full band interference sharing*. This plan called for all of the systems to operate over the whole spectrum [IWG1, 1993]. Since CDMA systems are designed to operate in noisy environments by spreading each signal, they would be able to coexist in this spectrum, but this type of plan would all but exclude Iridium.

In January 1994, the FCC finally decided to employ a combination of the two spectrum sharing proposals in order to allow sufficient access to the market for all the qualified systems. The final proposal, which the FCC said would accommodate up to five, and at least two, systems, split the L-Band into [Satellite News, 1994]:

- the lower 5.15 MHz for a TDMA system (Iridium); and
- the upper 11.35 MHz to the CDMA systems on a shared basis.

The full 16 MHz available at S-Band would be shared amongst the CDMA applicants. Financially, the FCC adopted requirements that the applicants would need to "demonstrate their ability to construct, launch, and operate their systems for one year" [Satellite News, 1994].

In addition to specifying a frequency sharing scheme and setting strict financial requirements to ensure the ability of the applicants to finance their systems, a number of other technical requirements mandated [Satellite News, 1994]:

- a low or medium earth orbit design, thereby excluding GEO systems from those frequencies;

- the ability to provide *global service;*
- the ability to provide *continuous service* throughout the United States;
- the first satellite be under construction by the end of the first year of the license; and
- service must begin by the sixth year of the license.

The FCC defined *global service* to mean "at least one satellite will be visible between 55° south latitude and 70° north latitude at elevation angles of 5° for 18 hours every day" [MCHI, 1994]. In order to provide *continuous service in the United States* a constellation must ensure the "visibility of one satellite, 24 hours per day, at a minimum 5° elevation angle" within the United States (between approximately 18° N and 70° N) [MCHI, 1994].

If offered a license, the applicants would be "issued a ten-year license from the date of the first launch, and blanket licensing for transceiver terminals" [Satellite News, 1994]. Comments on the proposal were requested from the applicants by May fifth [Satellite News, 1994], and the FCC finally adopted their proposal on October 14, 1994, when they put forth *Report and Order in CC Docket No. 92-166.* This announcement "adopted final rules for the licensing and operation of low Earth orbit mobile satellite systems above 1 GHz ("Big LEOs") that would provide a variety of voice and data mobile satellite services worldwide" [FCC, 1994]. In order to be considered for licensing, each applicant needed to file an amended (or new) application with the FCC by November 16, 1994 that would meet all of the requirements put forth in January.

These new criteria definitely affect the MSS playing field. In order to qualify for a license to provide MSS services in the Big LEO frequency range (1610-1626.5/2483.5-2500 MHz), the FCC has explicitly called for systems utilizing nongeostationary satellites (although GEO-based designs could be allowed if

they did not interfere with non-geostationary systems [Morgan, 1995]). Although this limitation does not preclude licensing for MSS services in other frequency bands (i.e. frequencies generally allocated for GEO services), AMSC filed an application with the FCC to provide MSS services utilizing a constellation of MEO satellites, in case they are not allowed access to the Big LEO frequencies for their GEO-based, MSAT system.

The six companies (systems) that filed applications to the FCC by the application deadline were: Motorola Satellite Communications, Inc. (*Iridium*), Loral/Qualcomm Partnership (*Globalstar*), Mobile Communications Holdings, Inc. (*Ellipso*), Constellation Communications, Inc. (*Constellation*), TRW (*Odyssey*), and the American Mobile Satellite Consortium (*AMSC*); although AMSC did not file the financial portion of the application. On January 31, 1995, the FCC awarded licenses to Motorola, Loral/Qualcomm, and TRW to construct, launch, and operate their Big LEO satellite systems. The Constellation Communications and MCHI filings were deferred until January 1996, due to a perceived deficiency in their financial qualifications. AMSC can also be considered for a license in January 1996 if they file the financial qualifications portion of their application.

2.3 Brief Overview of Proposed Systems

Each of the proposed systems plans to supply global voice services to handheld users in radically different ways. Table 2-4 displays a summary of some of the key design characteristics of each system.

Table 2-4 **Summary of the Proposed Systems**

Proposed System	Number of Satellites[1]	Altitude[1] (km)	Inclination[1] (°)	Satellite Dry Mass[1] (kg)	Satellite Power[1] (watts)	User Costs[3] ($/min, FY94)
Iridium	66	785	86.4	698	670	3 + tail
Globalstar	48	1414	50	426	823	0.6
Constellation	**46**					~0.5 + tail
ECCO	11	1965	0	1064	2201	
other	35	2035	62	1064	2201	
Ellipso	**16**					~0.5 + tail
Borealis	10	520/7800	116.	625	2242	
Concordia	6	7800	0	650	2589	
Odyssey	12	10355	50	1254	3050	< 1
AMSC	12	10355	47.5	3050	4900	?
Inmarsat-P	10	10355	45	~1500	4683	~2
Tritium[2]	3	GSO	0	2812	?	?

[1] Taken from the FCC filings.
[2] Hrycenko, 1992.
[3] Hulkower, 1995.

2.3.1 Iridium (Motorola)

Iridium is probably the most ambitious of the Big LEO systems proposed to date. When Motorola Communications first filed with the FCC in 1991, the Iridium constellation design consisted of 77 satellites (hence the name Iridium) in low Earth orbit. The design has since been refined to provide better service with fewer satellites, and currently consists of 66 satellites traveling in 6 near-polar orbital planes equally spaced around the equator. Each plane consists of 11 satellites orbiting at an altitude of 785 km, equally spaced within the plane. The satellites will communicate with the public phone network like most other satellite systems - through Earth-based gateway antennas tracking the fast moving satellites - but they will also be networked together, actively routing individual calls through each other using intersatellite crosslinks.

Initially, the costs of the handheld terminal are expected to be around $3000 per unit, with usage charges of $3 per minute plus tail charges (charges added on to the call to pay for landing rights in the country, and usual land-line extension charges). Although these charges are a bit higher than the other applicants' estimates, the primary market for the Iridium system is expected to be the international business traveler.

Conservative estimates call for 2 million users by 2002, consisting mostly of business, government, and the military. Eventually, however, huge markets are anticipated, especially in areas without existing infrastructure [Kinni, 1994].

Although the initial Iridium proposal called for small satellites that could be launched from a Pegasus rocket [Hulkower, 1995], the satellites have grown, both in size and capability, so that the satellites will be launched from Long March 2C, Proton, and Delta 2 rockets. An illustration of the satellite is provided in the following figure.

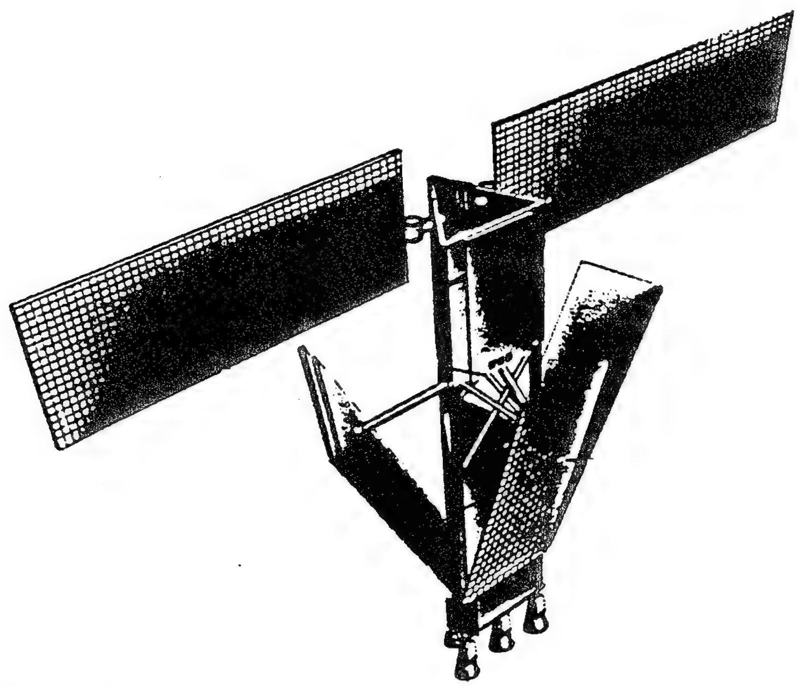

Figure 2-4 Illustration of an Iridium Satellite [Motorola, 1994].

As stated previously, Motorola plans to utilize a channelized Time Division Multiple Access (TDMA) scheme; however that scheme is further complicated since the uplink (Earth-to-space) and downlink (space-to-Earth) communication links will also share the same frequency band. This will require that the uplink and downlink channels each be assigned unique time slots, and each satellite

will take turns receiving and transmitting bursts of communications from multiple users. This type of multiple access approach is called Time Division Duplex (TDD), and when combined with the intersatellite links will require precise timing of all aspects of the system - not a small feat since the 66 satellites will all be moving quite rapidly. Each of the 66 satellites will form 48 unique spotbeams on the surface of the Earth. These spotbeam patterns will be formed by three phased-array antenna panels, each forming sixteen separate spotbeams per panel.

Raytheon, Co. received a $122.6 M contract with Motorola to manufacture the antennas for the first 75 satellites with options to supply antennas for another 45 satellites [Mobile Satellite Reports, 1 Dec. 1994]. The Iridium partnership also includes Lockheed Missles and Space Co., who have a $700 M contract with Motorola to "develop and manufacture 125 satellite busses for the system" [Defense Daily, 17 Nov. 1994]. Other developers of the Iridium system include Scientific-Atlanta, who will build ten telemetry, tracking and control terminals under a $15 M contract with options to build 30 gateway terminals for an additional $20 M [Scientific-Atlanta, 1995]; COM DEV of Canada, who will develop the intersatellite crosslink communication network; and Martin Marietta, Co., Bechtel Group, Inc., and Siemens Corp., who will develop other aspects of the system [Kinni, 1994].

In order to achieve these ambitious plans, the Iridium partnership has developed an assembly plant capable of producing a satellite in 22 days, and putting them out the door every five days [Scott, 1995]. Motorola plans to build 80 satellites in two years, launch the first satellite into orbit in 1996, and launch the rest in the next two years so that the $3.4 B first generation system can be operational in 1998 [Wu, 1994].

2.3.2 Globalstar (Loral/Qualcomm)

The Globalstar system is a LEO constellation proposed by Globalstar L.P. (Loral/Qualcomm Partnership). The Globalstar venture is owned by a new public company called Globalstar Telecommunications LTD, and a consortium of companies led by Loral Co. and Qualcomm Inc. The proposed system consists of 48 satellites orbiting at 1410 km in eight inclined orbital planes equally spaced around the equator. The eight orbital planes, each containing six equally spaced satellites, will be inclined 52° from the equator. The following figure illustrates a Globalstar satellite.

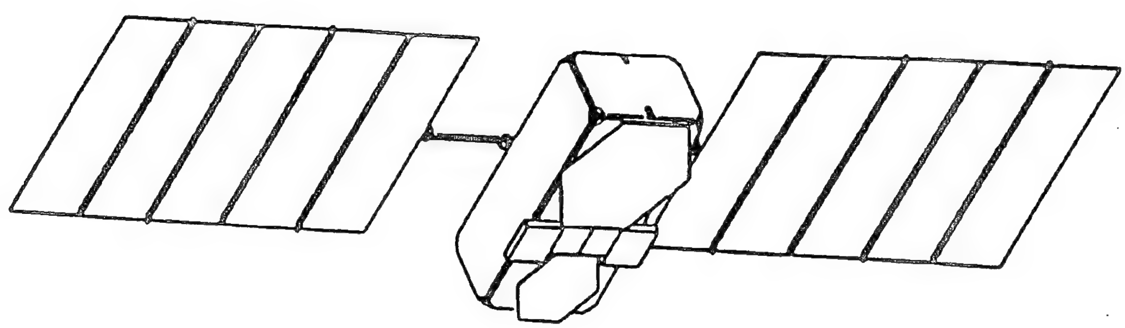

Figure 2-5 An Illustration of a Globalstar Satellite [Gaffney, 1994].

Although also proposing to provide services from LEO, the Globalstar system differs greatly from the Iridium proposal. One of the main differences lies in their market strategy. Unlike Iridium, the Globalstar system aims to become the lowest cost service provider [Berry, 1995; Seitz, 1995], proposing usage charges as low as 60 cents a minute [Hulkower, 1995]. The early handsets will cost approximately $750, and monthly usage charges will range from $8 to $100

[Hulkower, 1995]. Approximately 2.7 M Globalstar customers are expected by 2002 [Mason, 1994].

Although 48 satellites could still be considered a large number when compared to current systems, Globalstar aims to keep the costs down by providing a very simple design. Instead of using complex intersatellite crosslinks, the Globalstar satellites will provide communications services by functioning as a dumb, "'bent-pipe' transponder, receiving signals from a phone on the ground and passing them back to any gateway within the 1,500-mile-wide footprint, linked to locally available telephone networks" [Gilder, 1994]. Communications will be provided by a phased array antenna designed to form 16 individual spotbeam footprints per satellite. Globalstar will utilize a Code Division Multiple Access (CDMA) scheme based on Qualcomm's cellular standard to provide voice communications to the mobile user.

Space Systems/Loral has a contract for $896 M to produce the first 56 Globalstar satellites at an average cost of $16 M per satellite [Loral/Qualcomm, 1995]. Alenia Spazio of Italy will be responsible for the integration of the 56 satellites, and Finmeccanica Space Systems Co. will produce and test the 112 antennas installed on the satellites [Finmeccanica News, 1995]. Other major developers of the Globalstar system include Aerospatiale and Alcatel Espace of France, and Daimler Benz of Germany [Communique, 1995].

The first satellites are expected to be delivered by the end of 1996 [Finmeccanica News, 1995]. Globalstar plans to take six years to develop and launch the $1.95 B system [Seitz, 1995]. The first launch is expected by the fourth quarter of 1997, and the system is planned to reach full operational capability by the beginning of 1999 [Communique, 1995].

2.3.3 Constellation (Constellation Communications)

Constellation Communications first filed with the FCC to receive a license to provide MSS in the United States in June 1991, using a LEO-based system named *Aries*. *Aries* would have consisted of 48 satellites, located in four circular, polar orbital planes (12 satellites per plane) [Summers, 1992]. This LEO system was to operate at an altitude of 1020 km. Recently, Constellation Communications filed a substantially different design in their revised application to the FCC on November 16, 1994.

The new proposal, dubbed *Constellation*, consists of 46 operational satellites located in two MEO subconstellations [Constellation Communications, 1994]. The first constellation consists of a single, equatorial ring of eleven satellites equally spaced in a 1965 km circular orbit. Although their Brazilian partner, Telecomunições Brasileiras S.A., calls the constellation ECCO for Equatorial Constellation Communications, CCI has said a name has not yet been determined [Space Business News, 31 January 1995]. ECCO is paired with a second constellation consisting of seven planes of five satellites per plane orbiting at an altitude of 2035 km. Such a constellation of equally-spaced circular planes of satellites is often referred to as a Walker delta pattern since J.P. Walker of the British Royal Aircraft Establishment developed such constellations in order to allow continuous global coverage with a minimum number of satellites [Walker, 1973].

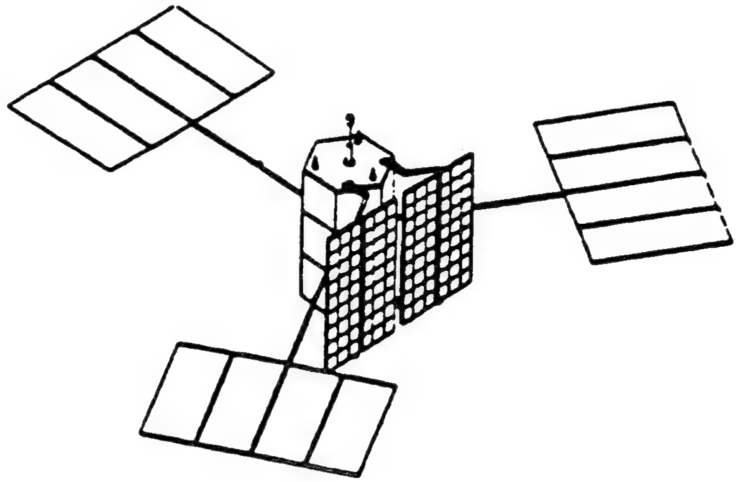

Figure 2-6 Illustration of a Constellation Satellite

Although Constellation did not yet receive a license from the FCC to provide services in the United States, they are waiting to see if they will be awarded one early next year. In the meantime, they may launch 12 satellites, one operational and one spare, into orbit so that they can provide services in the tropical regions by 1998 [Space Business News, 31 Jan. 95]. Martin Marietta Astro Space will build the satellites, and E-Systems will be the systems integrator [Space Business News, 31 Jan. 95].

2.3.4 Ellipso (Mobile Communications Holdings, Inc.)

The Ellipso system, whose constellation was designed by John Draim at MCHI, is the most unique system proposed to date. Ellipso is composed of two subconstellations, dubbed Borealis and Concordia. Borealis consists of two sun-synchronous, elliptical orbits with five satellites per plane. According to MCHI, the "ELLIPSO orbits have been carefully tailored and integrated to provide coverage quality and intensity that is proportional to the distribution of the world's population by latitude, and that favors daytime (peak period) service over nighttime (off-peak period) service" [MCHI, 1994]. MCHI is able to concentrate coverage during peak usage times through their use of sun-synchronous orbits. (Sun-synchronous refers to the fact that the relationship

between the orbital plane and the Earth-Sun line will remain the same over time).

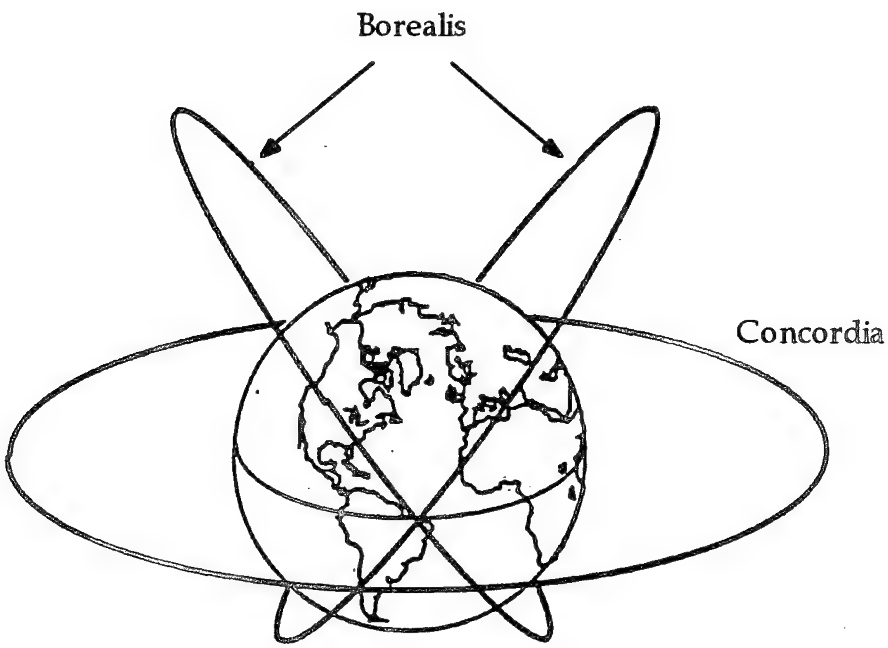

Figure 2-7 Ellipso Constellation

The Concordia subconstellation was supplemented to Borealis in order to provide service to the tropics, covering latitudes from 55° S to 45° N. Concordia consists of six satellites equally spaced in a single circular, equatorial plane. The combination of the Concordia and Borealis subconstellations is depicted in Figure 2-7. The service provided by the Concordia and Borealis constellations will overlap between 20° and 40° North latitudes, "providing flexibility in the application of satellite resources in this highly populated latitude belt" [MCHI, 1994].

Ellipso claims it can operate profitably serving an initial market size of fewer than 600,000 users, and are initially targeting 250,000 users in the United States and 350,000 users in the rest of the world [Brosius, 1994]. User costs would be around 50 cents a minute, and initial terminal costs will range from $700 per unit

for a handheld terminal to $1,200 per unit for a transportable unit [Hulkower, 1995].

Ellipso plans to operate as a bent-pipe transponder, using CDMA techniques, and 37 to 61 spotbeams. At apogee, the Borealis satellites would use only 37 beams "with the full complement of 61 beams being used when the satellites are lower than apogee" [MCHI, 1994].

The satellites are estimated to cost approximately $256 M, while the launch segment and first year of operations would cost $300 M and $8 M, respectively [Hulkower, 1995]. First launch is expected in mid-1997, although MCHI must also wait until early 1996 to see if it will receive a license from the FCC to operate in the United States.

2.3.5 Odyssey (TRW)

The Odyssey system, proposed by TRW, consists of a constellation of twelve satellites placed at MEO altitudes. The constellation initially proposed by TRW consisted of four satellites at 10355 km altitude in each of three circular planes inclined at 55°. TRW's refiling reduced the orbital inclination of the system to 50°, presumably to provide better coverage at lower latitudes.

TRW also plans to offer the lowest price service, and aims to be the first system to market - although that will not happen if Motorola stays on schedule [Eastwood, 1994]. TRW predicts that they will be able to offer usage rates at 65 cents per minute plus 10 cents per minute in access fees [Dornheim, 1994]. Initial handset prices should vary between $250 and $300 per unit, and monthly access charges are estimated at $24 [Dornheim, 1994]. "Odyssey attributes its lower rates to lower startup costs from fewer satellites, longer satellite life (ten vs. five to eight years), and directed antenna coverage that keeps users in sight of two satellites at all times" [Telecommunications].

In November 1994, TRW announced a joint venture together with the Montreal telecommunications firm, Teleglobe, Inc., to develop and supply the Odyssey services. The Odyssey satellites and ground sites will be built by TRW, while Teleglobe will market the Odyssey services worldwide [Dornheim, 1994].

The Odyssey satellite will provide downlink communications through 37 individual spotbeams formed from a 5.2 foot parabolic reflector [Dornheim, 1994]. The uplink signals will be received from an 8 foot reflector [Dornheim, 1994]. The Odyssey system, like Globalstar, does not utilize onboard processing or satellite crosslinks but merely operates as a bent-pipe repeater [TRW, 1994]. TRW plans to launch the satellites two at a time on Atlas-2AS class boosters [Dornheim, 1994].

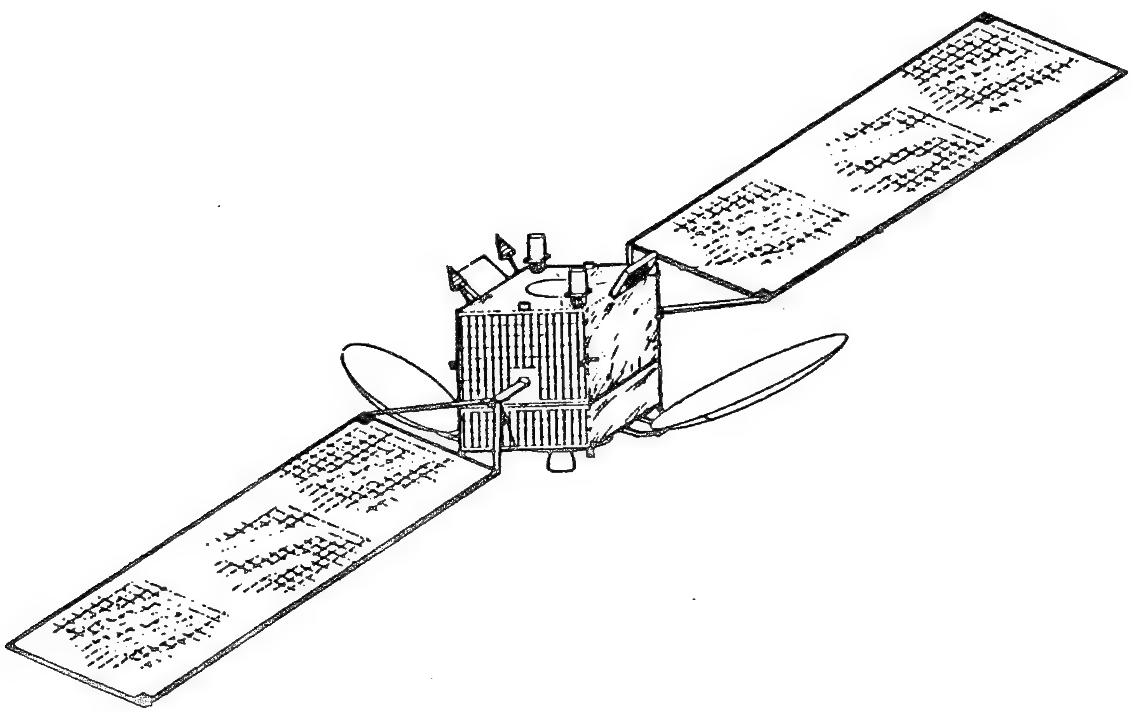

Figure 2-8 Illustration of an Odyssey Satellite [TRW, 1994].

TRW and Teleglobe plan to begin providing "service in 1998 with only six satellites in orbit" [Telecommunications, 1994], and also claim that continuous,

single satellite coverage can be provided in some regions with a system of nine satellites (three satellites in each plane). The full system of twelve satellites, developed and launched within six years, will provide full operational capability and ensure that "two or three satellites are visible at all times and service can be provided to most of the world's land mass" [Rusch, 1992]. The full $1.8 B system should be operational by the end of 1999 [Dornheim, 1994].

2.3.6 AMSC

The American Mobile Satellite Consortium (AMSC), formed in 1988, launched a single geostationary satellite on April 7, 1995 to provide mobile satellite services in the United States and Canada [Business Wire, 1995]. "AMSC 1 is scheduled to begin servicing existing and new customers in the 3rd quarter of 1995 with a full range of mobile satellite services to the United States market" [Business Wire, 1995]. Although meant to provide domestic voice services, the MSAT design does not allow for the use of handheld antennas - only vehicular-mounted and transportable briefcase phones [Seitz, 1995]. Although AMSC already has a license to provide MSS in the U.S. through MSAT using other frequency bands, they have been pushing the FCC to get "permission to use Big LEO frequencies for its geostationary satellite-based domestic system." AMSC plans to expand their MSS system to a total of three satellites. In 1989, the FCC originally authorized AMSC to launch three GEO satellites to service North America, but "the company has filed for five extensions" [Seitz, 1995]. Although AMSC plans to launch these other satellites eventually, since they expect AMSC 1 to be operating at capacity soon after it comes on-line in September 1995, the other Big LEO companies have been pressuring the FCC to revoke their licenses [Seitz, 1995].

The FCC's Report and Order has required non-GEO-based system designs for license applications to provide MSS services in the Big LEO frequency bands (1.6/2.4 GHz). In an apparent attempt to keep themselves in the running to

provide MSS services in these bands, AMSC filed with the FCC for a license to operate a constellation of twelve MEO satellites, very similar to the Odyssey system. The system will consist of six satellites (five operational and one spare) in each of two, 5.98 hour, circular orbits at an inclination of 47.5°.

2.3.7 Inmarsat-P

As part of its continuing evolution to provide communications services to mobile users, Inmarsat has conducted detailed technical and marketing studies to determine what system characteristics would be desired to provide personal communications services from satellites into the next century. As part of that study, contracts were awarded to multiple companies to complete point designs of LEO, MEO and GEO systems in order to narrow in on the best orbital configuration for their system. In July 1993 Inmarsat decided to stop looking at the LEO option due to its high perceived costs and inferior coverage characteristics. In May 1994, Inmarsat finally chose a MEO configuration as the architecture for their future Inmarsat-P service. The choice was made primarily due to the high elevation angles available to MEOs, the greater number of satellites in view to the user, long service life, acceptable signal delay, and the reasonable cost.

The Inmarsat-P design calls for a constellation of ten satellites in two orbital planes. The Inmarsat-P satellites will orbit at an altitude of 10,355 km, and an inclination of 45° [Jurkiewicz, 1995]. If the market expands as hoped, Inmarsat may add a third plane with more satellites to improve the system capacity [Lundburg, 1995].

Inmarsat "decided to form a private company to run the hand-held Inmarsat-P project" [Khadem, 1994]. The purpose behind this decision was to provide flexibility to Inmarsat investors since under the old structure "an investor's share in Inmarsat would dictate how much it would have to commit to this project"

[Khadem, 1994]. Another possible reason to turn private is to "distance Inmarsat-P from the government status of its parent organization," since many of the Big LEO companies and the United States government have concerns that "many Inmarsat members operate as monopolies on their national territories and will be able to lock out Inmarsat-P competition" [de Selding, 12-18 December 1994].

On December 9, 1994, representatives from 56 countries endorsed the plan to create the Inmarsat-P affiliate and compete with the Big LEO services. In early 1995, the Inmarsat-P affiliate was able to raise $1.4 B in first round financing from 38 signatories to the astonishment of most people in the industry [Satellite News, 1995]. Comsat "became the biggest investor in Inmarsat-P with a $147 million investment" [Satellite News, 1995].

The Inmarsat affiliate has decided to utilize the 2.0/2.2 GHz frequency bands set aside for mobile services during WARC-92. Although those bands are not to become available until 2005, the affiliate is pressuring the ITU and the world community to open those bands earlier. Inmarsat wants to avoid the standard RDSS bands since they are expected to be horribly overcrowded with all of the other proposed systems [Lundburg, 1995].

Although the Inmarsat-P satellite design has not been publicly finalized yet, the system will probably use TDMA and operate as a bent pipe since it will offer the system more flexibility to adjust with the market. The satellite is expected to provide between 120-150 spot beams, although designs with as few as 85 and as many as 241 beams have been considered. The satellite design will either utilize separate 2.2 m receive and 1.7 m transmit antennas, or one combined transmit and receive antenna [Lundburg, 1995]. Figure 2-9 displays an example of the two antenna design choices.

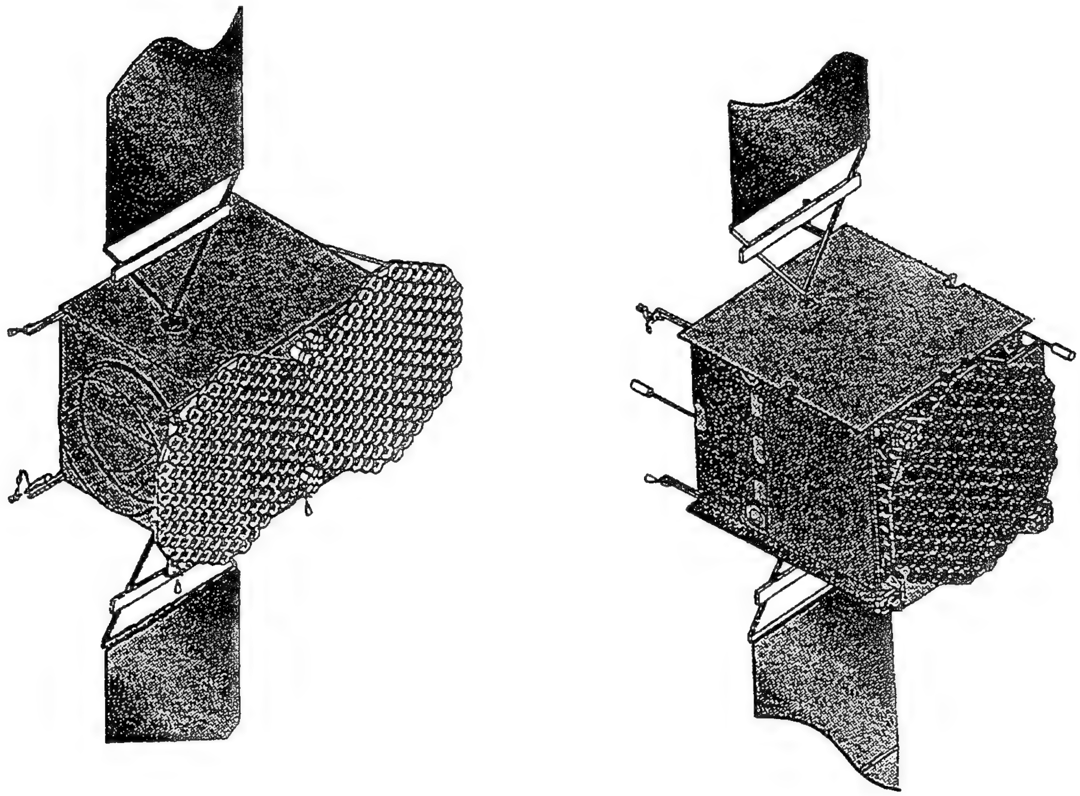

Figure 2-9 **Possible Inmarsat-P Antenna Configurations [Jurkiewicz, 1995].**

Although they have not received a license to operate anywhere yet, Inmarsat-P is moving forward fast. They recently signed a $1.3 B contract with Hughes Space and Communications, who will build twelve HS-601 satellites for the Inmarsat venture [Inmarsat, 1995]. The satellites will be compatible with the new Delta III launcher, as well as the Ariane, Atlas Centaur, Proton, Zenit or Long March boosters [Inmarsat, 1995]. The Inmarsat-P affiliate plans to begin service at the turn of the century after launching their satellites in 1998 and 1999.

2.3.8 Tritium (Hughes)

In late 1991, Hughes Aircraft Company proposed a geostationary constellation named *Tritium*, in response to the *Iridium* proposal, to show that mobile satellite services could be provided more efficiently at GEO. In addition to providing comparable performance as the LEO proposals, Hughes contended that a GEO-

based satellite system could be provided with "more conventional technology, ... less operational complexity," and at a "substantially lower cost" [Hrycenko, 1992]. Full global coverage (outside the polar regions) can be provided with only three geostationary satellites, while LEO systems require many times that number. Hughes proposed placing the satellites at 100° West, 20° East, and 140° East longitude.

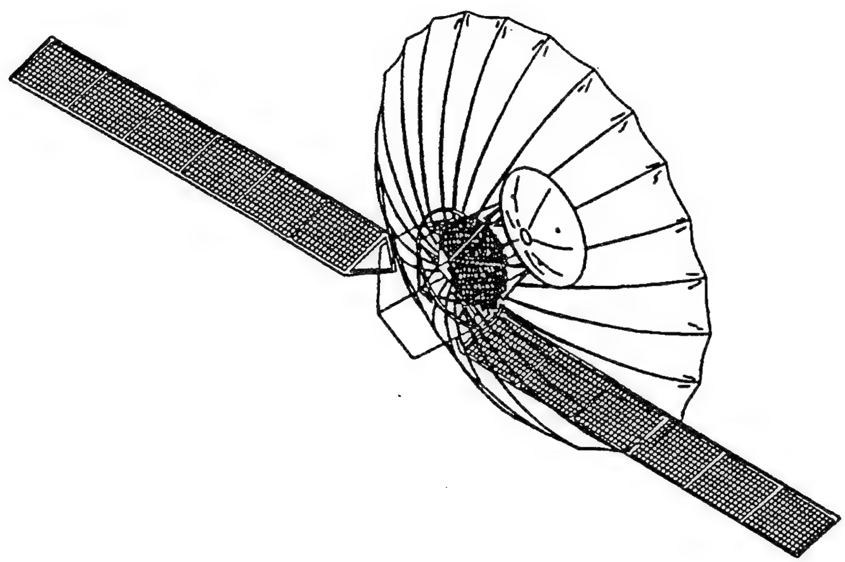

Figure 2-10 Illustration of a Tritium Satellite [Hrycenko, 1992].

The Tritium proposal, also using CDMA multiple access technology, would require a large number of spotbeams (around 160), and large 55 foot diameter parabolic reflectors. Although Hughes is not currently developing a system under the name of *Tritium,* they have been aggressively pursuing the implementation of regional mobile satellite services throughout the world. In addition to their involvement with AMSC's MSAT system in the U.S., "Hughes and Singapore Telecom have announced plans to operate a geostationary-based mobile satellite system over Asia" [Telecommunications, November 1994]. It is not clear, however, whether Hughes will continue pursuing regional GEO-based

mobile satellite systems now that they have won the contract to build the twelve satellites for the Inmarsat-P affiliate [Inmarsat, 1995].

2.4 LEO vs. MEO vs. GEO

The concept of communicating through satellites has been around since Arthur C. Clarke first proposed the idea to provide global communications using three geostationary satellites in 1945 [Clark, 1945]. A satellite in geostationary orbit is placed in an equatorial orbit at an altitude that matches the angular velocity of the satellite with the angular velocity of the Earth. Since the satellite appears to hang motionless over the same point on the Earth's surface, it can act as an extremely large communications tower that has visibility to a third of the Earth's surface.

The diverse applications received at the FCC in the past few years to provide mobile satellite services have rekindled a debate in the industry on whether either LEO-, MEO- or GEO-based communications systems can inherently service the mobile satellite market better. Although the debate has recently surfaced, the question is certainly not a new one. The earliest communications satellites (SCORE, ECHO, Courier, Telstar, etc.) were all placed in LEO and MEO orbits due to launch vehicle limitations. The debate between LEO, MEO and GEO systems first surfaced in the early 1960's when military and commercial interests were planning the first operational communication satellite systems [Wu, 1994; Pritchard, 1964]. The early altitude debates were concerned primarily with tradeoffs between ground tracking, attitude control, launch vehicle performance and reliability, and the signal delay. The lower altitude systems required ground antennas that could track fast moving satellites, and raised concerns of launch reliability due to the large number of satellites required. The GEO systems, however, raised the issue of launch performance and reliability, and the concern with the signal delay associated with the long transmission path to GEO [Pritchard, 1964]. Since launch vehicle performance

and reliability was low (~50%), and attitude control and stationkeeping was primitive, one of the early tradeoffs involved a comparison of GEO-based system (requiring a minimum of 6 satellites), with a system of MEO satellites (18-24 satellites) placed in random orbital positions [Pritchard, 1964]. Although the debate involved many different factors, the GEO-based communications systems became the preeminent standard in the industry, with the deployment of the commercial Syncom series, and the military IDCSP series [Martin, 1991]. Despite the virtual dominance of GEO systems in the last 30 years, however, a small number of LEO and MEO satellites have been launched every year for specialized military and commercial purposes, low cost experiments, and for amateur radio hobbyists [Martin, 1991]. Figure 2-11 clearly illustrates this trend, showing the final altitude of a large number of communications satellites launched in the last 40 years.

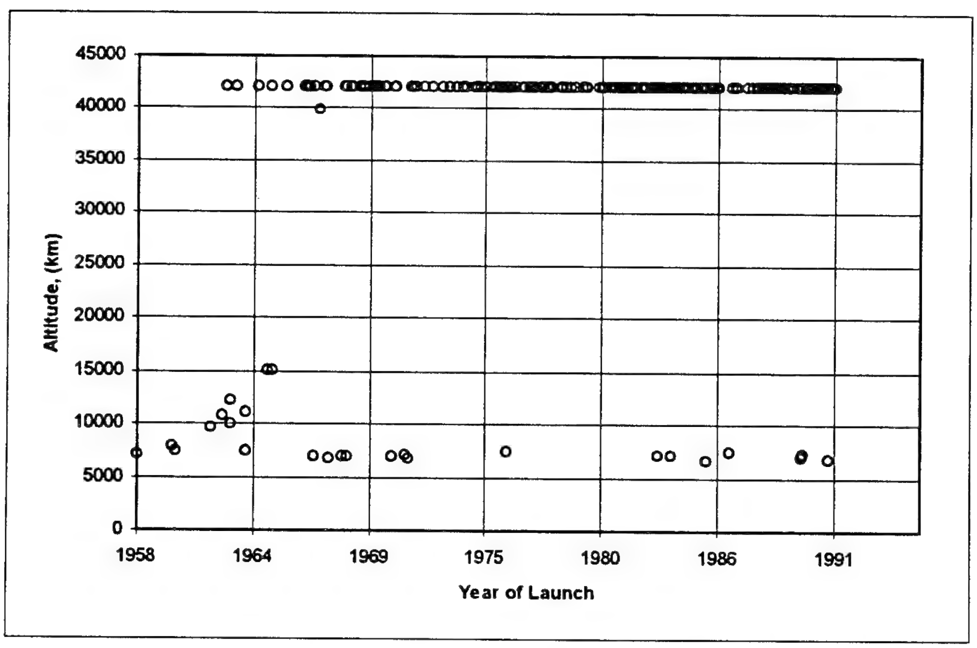

Figure 2-11 **Communications Satellite Altitudes in the Last 40 Years [Martin, 1991].**

As discussed previously, the advancement of technology witnessed by the ever shrinking communications terminal has enabled communications with satellites

using handheld terminals. Due to many trends in the industry, including a tremendous resurgence of interest in developing low cost small satellites, the recent availability of small launchers such as Pegasus, and the flurry of applications to provide satellite-based services from nongeostationary orbits, the LEO vs GEO debate has been rekindled. Much of the debate mirrors the early arguments for and against each system advocated during the early 1960's. A useful way to summarize the debate is to survey the arguments put forth by the proponents of the Big LEO systems.

All of the proposed non-geostationary mobile satellite systems have brought up similar arguments against the use of GEO-based MSS. The main issues put forth, derived from a number of sources [Motorola, 1991; Rusch, 1995; Lundberg, 1995; Dorfman, 1993; Johannsen, 1994; Hulkower, 1995], include the following.

2.4.1 Transmission Delay

One of the main arguments against the use of GEO satellites for mobile communications, or any communications for that matter, involves the issue of signal, or transmission delay. This concern stems from the fact that a signal traveling from a user on the ground to a GEO satellite directly above will take approximately 125 ms to reach the satellite and another 125 ms to repeat the trip back. As the user moves further from the satellite's nadir position, so that the elevation angle to the satellite decreases, the transmission delay increases further.

The concern with increasing signal delay has to do with the perceived reaction of the users. The problem with signal delay does not entirely have to do with the delay itself, but often with the echo associated with it. Study of signal delays and echoes in communications media date back to the 1920s and 1930s, when communications were first attempted across long distances [Emling, 1963]. Because the equipment was slower than it is today, objectionable delays were

Because the equipment was slower than it is today, objectionable delays were inherent in the system, and echoes were introduced by the equipment itself [Emling, 1963]. Voice echoes can occur when local circuits are not properly balanced in impedance with the network [Emling, 1963]. As a signal travels to the juncture between transmission lines that are not properly impedance matched, a portion of the signal will be echoed back to the calling party [Emling, 1963]. These problems caused the phone companies to develop echo suppressers that were able to suppress the signal echo [Emling, 1963]. Signal delay studies came back to the forefront of communications in the early 1960's when the world was deciding whether to provide their new satellite communications networks from LEO or GEO orbits. It turns out that echo suppressers have a harder time masking the signal echoes as the signal delay increases. Although the world finally decided to go GEO, and modern day echo suppressers are much more robust than their earlier counterparts, many of the LEO proponents feel that the long signal delays to GEO will be objectionable to the modern user.

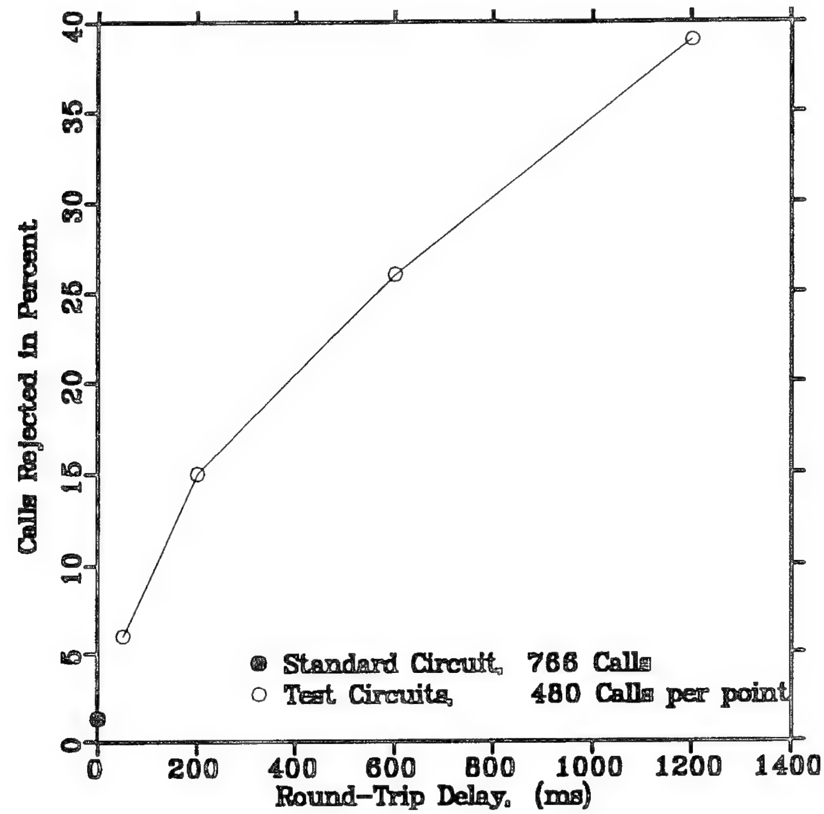

Figure 2-12 Telephone User Rejection Rate as a Function of Round Trip Transmission Delay [Riesz, 1963].

A number of user reaction studies have been conducted - many of them in the early 1960s - to determine how much delay and echo is acceptable to the user. Unfortunately, most of these studies have not been published; however the results of those that have are varied. Figure 2-12 displays the results of one of those studies. This study, published in the Bell System Technical Journal, measured the user rejection rate of telephone calls at four different delay times, and using four different echo suppressers. The study suggested that the rate of call rejection increases greatly with the length of the delay. In addition, the study reported that the rejection rate increased with the length of the call, but that user tolerance of delay did not increase with experience. An alternate view of the situation has been put forth by Comsat Laboratories, however. Comsat simulated the effects of transmission and processing delays for satellite orbits ranging from LEO to GEO, and found that the quality of the circuits did not vary

appreciably with altitude [Dorfman, 1993]. Other studies have reported mixed results.

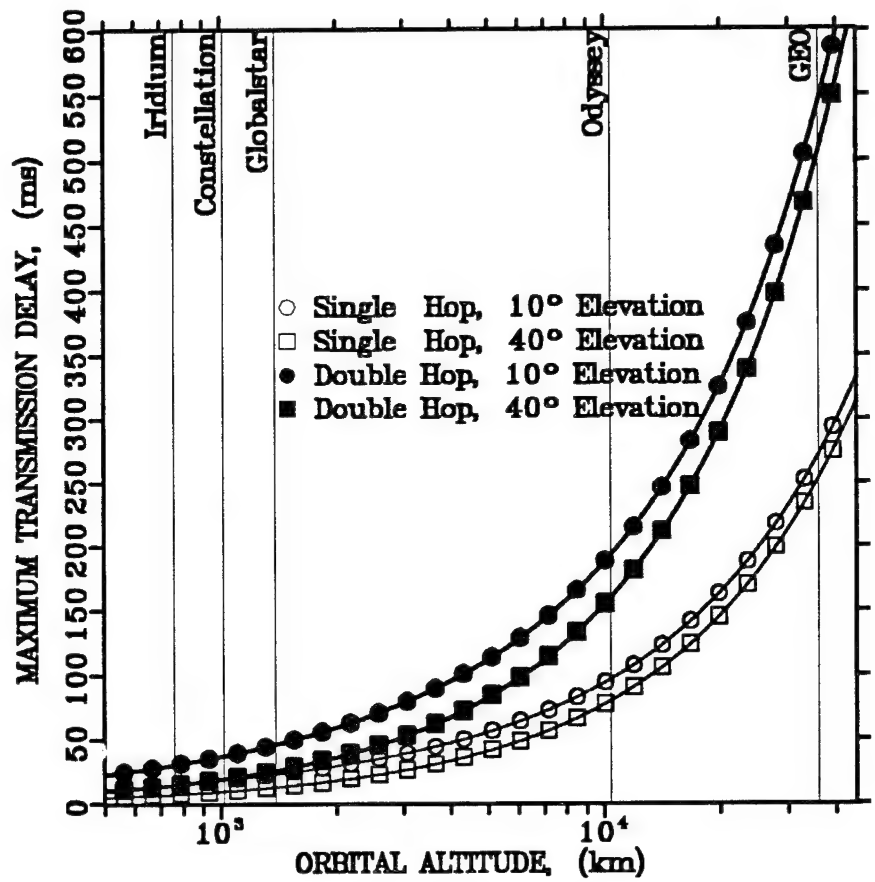

Figure 2-13 Maximum Propagation Delays for Mobile Satellite Systems.

Figure 2-13 displays the maximum single hop (through one satellite) and dual hop (through two satellites) propagation delay as a function of orbital altitude for two different elevation angles. The delays are considered maximum since they represent a transmission path from the edge of coverage (defined by the elevation angle) of the satellite to another point on the edge of coverage. As can be seen in the plot, the LEO systems experience very little delay, and the MEO systems suffer slight delays. The GEO delays, however, range from 250 ms to almost 600 ms for a dual hop.

Although the signal delay debate is far from settled, even GEO proponents agree that the delays associated with a double hop make mobile-to-mobile traffic unacceptable for a GEO system, [Johannsen, 1994] although that type of traffic is not expected to be very significant. Since many of the expected users are "those who have no telephone service at all, and those whose only service comes from geosynchronous spacecraft," Hughes expects they would still utilize the system in the absence of better quality solutions [Hrycenko, 1992].

2.4.2 High Latitude Coverage

The next argument against the use of geostationary systems regards their poor coverage at the higher latitudes. The further north or south in latitude a user is located, the lower in elevation the satellite will appear in the sky. Lower elevation angles correspond to a greater likelihood that a signal will be blocked by buildings, trees, or other obstructions, and a corresponding reduction in the availability of the system. In addition to low elevation angles, geostationary satellites are unable to provide service of any kind to users above approximately 70° in latitude since the satellites will appear beyond the horizon.

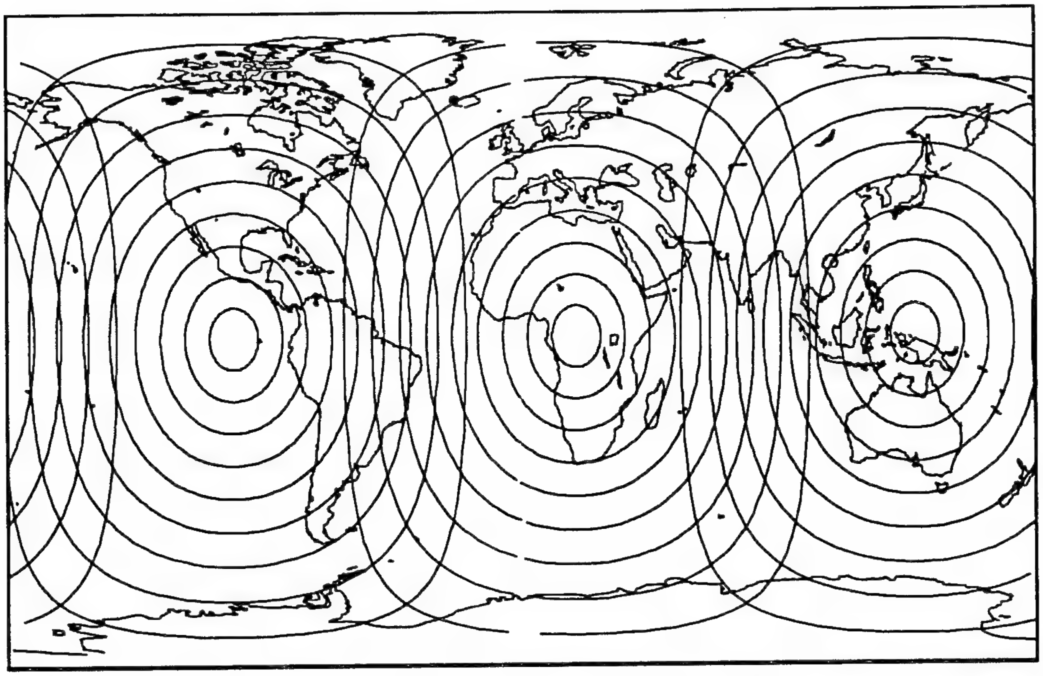

Figure 2-14 Coverage Contours for the Tritium System.

Figure 2-14 displays coverage contours for the proposed Tritium system. The three small circles along the equator represent 80° coverage contours for the three Tritium satellites (i.e. a satellite would appear within 10° of zenith to a user located inside one of the circles). Each larger concentric ring represents an increase in elevation of 10°. The outer rings represent the outer edge of the satellite coverage zones, and users located outside of the zones will be unable to see the satellites. Although few users are expected beyond the outer concentric ring, many MSS proponents feel that elevation angles from 10° to 20° are necessary to provide adequate service to mobile users [Rusch, 1995; Lundburg, 1995]. Requiring a minimum 20° elevation angle coverage would leave Alaska and much of Canada, Scandinavia and Russia without adequate coverage. Hughes argues that few users are expected at high latitudes and suggests that less than 0.5% of the world's population (mostly in Russia) would be unserved by a GEO-based system [Hrycenko, 1992].

2.4.3 Complex and Expensive Satellites

Another traditional argument involves the notion that a GEO satellite is very large, complex and expensive. Since satellite and launch costs generally scale with satellite mass, it is likely that individual GEO satellites will be more expensive. LEO or MEO satellites are expected to make up for their larger numbers by using smaller satellites, which should correspond to lower satellite and launch costs. It is not inherently obvious which type of system is cheaper, however, since GEO systems would need three or four satellites, while some of the LEO systems require up to 66 satellites. Hughes disputes that a Tritium-like system would be more expensive to implement than a LEO system. They argue that fewer satellites, although more expensive individually to produce and launch, will cost less in the end than the large number of satellites required at LEO. Indeed, since GEO satellite lifetimes are approaching 15 years, the five to seven year lifetimes at LEO will require even more satellites to continue service.

2.4.4 Spectrum Efficiency

The currently available spectrum for mobile satellite services is limited, consisting of only 32 MHz of bandwidth split equally between the L and S-bands. Since the available bandwidth is at a premium, projected satellite systems must make efficient use of the spectrum. Multiple signals transmitted to a user in the same frequency band will produce interference, making it difficult for the user terminal to understand either signal. For this reason, satellite communications systems must find ways of reusing the available spectrum so that this interference is avoided, while still satisfying an adequate number of users.

One of the main ways to reuse the spectrum is to separate the signals spatially (See Chapter 5). This can be accomplished by using separate satellites, or by separating each satellite's coverage area into unique cells of coverage called spotbeams. Spotbeams are able to concentrate the focusing gain of the antenna

in a single area, so that the same frequencies can be reused in non-adjacent beams. Since the number of spotbeams on a GEO satellite is limited by both satellite real estate (spotbeam hardware requires space) and interference issues, it is argued that LEO systems will be better able to reuse the spectrum.

GEO proponents dispute this claim, arguing that although the Iridium system provides more spotbeams, many of them will cover ocean areas with few users, and many others will be turned off when near the poles due to beam overlap, resulting in a channel usage efficiency of 18%. Stationary GEO systems, on the other hand, can be more flexible with the market since satellites can be moved and spotbeams modified, to directly focus capacity where the traffic demands. Additionally, the system can be built up slowly to match the market growth, while LEO systems will require a large number of satellites in orbit before service can begin.

2.4.5 Service Continuity

Due to the few number of satellites required at GEO, a single satellite failure can cause significant, long-term outages to up to a third of the world. Since ground spares would take too long to replace the errant satellite, on-orbit spares would be required. LEO systems, on the other hand, are considered inherently robust due to their greater numbers. Single satellite failures in a LEO system, however, would create short coverage gaps (on the order of 10 to 20 minutes) a few times a day. On-orbit spare satellites would be able to fill the gaps in a few days.

MEO systems sit in the middle of the LEO vs. GEO debate, claiming to provide less expensive, more robust, and higher quality service than either the LEO or GEO systems. MEO systems argue they experience less signal delay, cost less to build and launch, and provide better coverage than GEO systems. Due to their higher altitude, however, they claim to provide superior coverage using fewer satellites than their LEO counterparts. The fewer satellites are expected to

translate into a lower system cost, and more cost effective services [Rusch, 1994; Rusch, 1995; Lundburg, 1995].

2.5 Previous Studies

With revenues projected as high as 17 $B [Herring, 1994], the race to provide mobile satellite services has been extremely competitive, and has prompted many studies in the last five years. Most of these studies have concentrated on highlighting the advantages and disadvantages of each orbital altitude, while others have concentrated on individual aspects of the proposed designs. The numerous studies range from general surveys, to comparisons of individual aspects of each system, to detailed technical comparisons of many aspects of each system. One of the largest and most detailed studies has been conducted by the MITRE Corporation. In their three volume report prepared for the European Space Agency, MITRE has surveyed the mobile satellite industry and conducted detailed evaluations of many of the proposed systems [Ciesluk, 1992a; Ciesluk, 1992b; Gaffney, 1994].

The first study, entitled "Survey of the Mobile Satellite Communications Industry," provided a detailed overview of all of the Little LEO and Big LEO proposals to date, and included an overview of the existing Inmarsat and imminent regional mobile satellite systems [Ciesluk, 1992a]. The second volume, entitled "An Evaluation of Selected Mobile Satellite Systems," was published as a companion volume with the first. This study conducted a detailed evaluation of a number of selected mobile satellite systems, including Iridium, Globalstar, Aries, Odyssey, and the next generation Inmarsat-3 system [Ciesluk, 1992b]. The large study included detailed validity checks on mass, power, coverage, launch strategy, and market size for each of the systems. In addition, the report provided an overview of the market, and an analysis of the aspects expected in a viable service. This pair of studies concluded that each of the MSS could be made to work technically, but that a "large LEO system offering the full range of

mobile services including voice may not be economically viable by the turn of the century, when it is most likely to be able to enter the market" [Ciesluk, 1992b]. In addition, the study found that MEO systems had some advantages over both LEO and GEO systems. In particular, MEO systems require fewer satellites to achieve worldwide coverage than LEO systems, and experience shorter time delays than GEO systems. In addition, the elevation angles achieved by the proposed MEO systems were found to offer far better coverage than their LEO counterparts [Ciesluk, 1992b].

The third volume of the MITRE study, published in 1994, presented an updated evaluation of four of the proposed Big LEO systems: Iridium, Globalstar, Ellipso, and Odyssey [Gaffney, 1994]. Much like the previous study, this analysis included independent validity checks on the proposed systems' technical and economic characteristics, including satellite mass and power, system availability, geographical coverage, cost and schedule. This study has since been updated by Neal Hulkower in March, 1995 [Hulkower, March 1995]. Most of the main conclusions of this study mirrored the previous study in that the proposed systems are expected to be able to work technically, although not necessarily within their claimed budgets [Gaffney, 1994]. In addition to these general conclusions, the MITRE study concentrated on highlighting the technical challenges faced by each of the systems since this area was of particular interest to the ESA.

In particular, MITRE questioned Globalstar's mass, cost and schedule claims, and observed that Iridium's production schedule is unprecedented and represents a substantial risk area. The Odyssey cost estimates were found to be reasonable although their schedule appeared somewhat aggressive. As before, several advantages of MEO systems over their LEO counterparts were highlighted, including [Hulkower, 1995]:

- *fewer spacecraft means not needing to establish a "mass" production facility;*
- *less frequent hand off between satellites required; and*
- *more favorable elevation angles.*

MITRE has suggested that terminal costs below $1500 per unit, and usage rates of less than $1.50 per minute would be required to achieve rapid penetration of the market, and that the Pacific Rim offered the largest potential MSS market.

One of the main hurdles expected for each of the systems involves the lack of a standard, worldwide spectrum allocation authority. Although the ITU assigns frequency allocations worldwide, systems will still be required to obtain spectrum allocation and landing rights in every region of the world that they plan to offer service. Other technical challenges highlighted by MITRE are listed in the following table as a function of the orbit class [Hulkower, June 1995].

Table 2-5 Technical Challenges for Proposed MSS [Hulkower, June 1995]

	LEO	MEO	GEO	HEO
Satellite producibility	x			
Operation in radiation belt		x		
Satellite antennas	x	x	x	x
Interference control	x	x		x
Earth station technology	x	x		x

The satellite producibility concerns affect the LEO systems, since they will be attempting a "serial production of satellites never attempted before" [Hulkower, 1995]. The MEO systems, since they will fly within the Van Allen radiation belts, will be exposed to high doses of radiation. Designing a satellite to operate in this harsh region will require a large increase in the size of the solar arrays needed since radiation exposure will degrade the performance of the solar cells. In addition, heavy shielding and expensive radiation hardened electronics may be required to survive in this region, which may also increase the mass and cost of the proposed systems. Satellite antennas were found to be a technical

challenge for all of the systems. GEO systems will require large and complex antennas to support a link to small handheld terminals, while all of the systems will be challenged to control sidelobe (antenna radiation outside of the focus region) interference between separate spotbeams and satellites [Hulkower, June 1995].

The other two technical challenges for the non-GEO systems highlighted by MITRE include interference control, and earth station technology. Interference control is expected to be an issue since procedures do not currently exist internationally to coordinate interference issues between nongeostationary systems. In addition, it is likely that the earth stations of some systems may interfere with the satellites from another system. Earth station complexity is an area that MITRE believes has been seriously underestimated. "This complexity involves the tracking, handoff and signal integrity for the multiple satellite constellations, and also involves the question of baseband interfaces and general access to the public switched telephone networks (PSTN) with which these systems will operate" [Hulkower, June 1995]. Although many of these problems have been addressed by fixed GEO systems, their experience has shown that these stations can be "quite complex and expensive" [Hulkower, June 1995].

3. *Methodology*

3.1 Methodology Overview

The main objective of this thesis is to evaluate the effectiveness of different system architectures to address the mobile voice communications market. This problem mirrors the types of capital budgeting decisions that corporations need to make every day in order to remain competitive. *Capital budgeting* refers to the "entire process of analyzing projects and deciding whether they should be included in the capital budget" [Dickerson, 1995]. A capital budget "sets forth planned expenditures on fixed assets and other long term projects by detailing projected inflows and outflows during some future period" [Dickerson, 1995]. These types of decisions can often be the most important ones a company will ever make, as a successful choice will enable them to become, and remain competitive in the marketplace. On the other hand, capital budgeting decisions can be harrowing, since a poor decision can devastate the largest of companies, as witnessed by the fall of Barings of London.

Long-term project investment decisions can be crucial as they frequently require large sums of money, limit the company's future flexibility, and require critical decision timing [Dickerson, 1995]. Entering into the MSS market certainly involves a huge investment for any company, with estimates for current

proposals ranging from $660 million (M) to $3.8 billion (B), as shown in Table 3-1.

Table 3-1 Projected First Generation MSS Deployment Costs

System	Operational Satellites	Projected Cost, ($M US)
Iridium	66	3759[1]
Globalstar	48	1554[1]
Constellation	46	1695[1]
Ellipso	16	764[1]
Odyssey	12	1844[1]
AMSC	10	3065[1]
Inmarsat-P	10	2600[2]

[1] Obtained from their FCC filings, November, 1994.
[2] Hulkower, March 1995.

The development and launch of a mobile satellite system requires the interaction of a complex network of satellite constellations, ground stations, and millions of handset terminals. With the added difficulty of requiring separate authorizations from a myriad of government and commercial agencies throughout the world, a company must find multiple sources committed to providing large sums of money to finance the effort. The FCC realized this constraint when it set strict financial requirements in order for a system to qualify for a license to provide mobile satellite services in the United States. With the minimal spectrum currently available for MSS internationally, each system applicant has been required to prove its ability to finance the effort.

Companies normally follow a standard process while making capital budgeting decisions, consisting of the following basic steps [Dickerson, 1995]:

1. Review goals and objectives;

2. Search for proposals;

3. Estimate cashflows of each proposal;

4. Rank the proposals;
5. Select the best project; and
6. Implement.

The evaluation of potential MSS architectures conducted in this study will follow the same overall process. The steps taken during this study can be classified as follows:

1. Determine what services the MSS should address;
2. Select potential architectures to evaluate;
3. Estimate system costs and potential revenue throughout the system's service life;
4. Rank the architectures by some set of criteria; and
5. Choose the best system(s).

Performing these steps for a complicated system requires a rigorous approach. Aspects of the Systems Engineering process cater for such an approach, as its systematic methodology was developed to enable the successful design of complex systems. The systems engineering process, which grew out of the complex weapons systems development environment, was pioneered in the aerospace industry by Lockheed Missiles and Space Company during the fleet ballistic missile programs of the 1950s. The process has since gained wide acceptance in both the military and aerospace communities, where its is currently practiced today [Patel, 1995].

Definitions of the systems engineering approach abound. One possible definition can be found in MIL-STD-499B [Chapman, 1992]:

> *Systems Engineering is the management and technical process that controls all engineering activities throughout the lifecycle in order to achieve an optimum balance of all systems elements to ensure satisfaction of mission requirements, while providing the highest degree of mission success. It has two main activities:*
>
> - *interpreting the customer's needs and translating them into a set of requirements that can be met by individual design and specialty disciplines; and*
>
> - *validating that the system satisfies the customer's needs through analysis, simulation and testing.*

In other words, systems engineering provides the framework to ensure that a design is customer-driven by translating customer preferences into a solid set of top level requirements that the system must satisfy. Although there are many other aspects and tools involved in the Systems Engineering process, its salient features can provide the rigorous approach needed to objectively evaluate different MSS architectures. The segment of the Systems Engineering Process applicable to this study is illustrated in Figure 3-1.

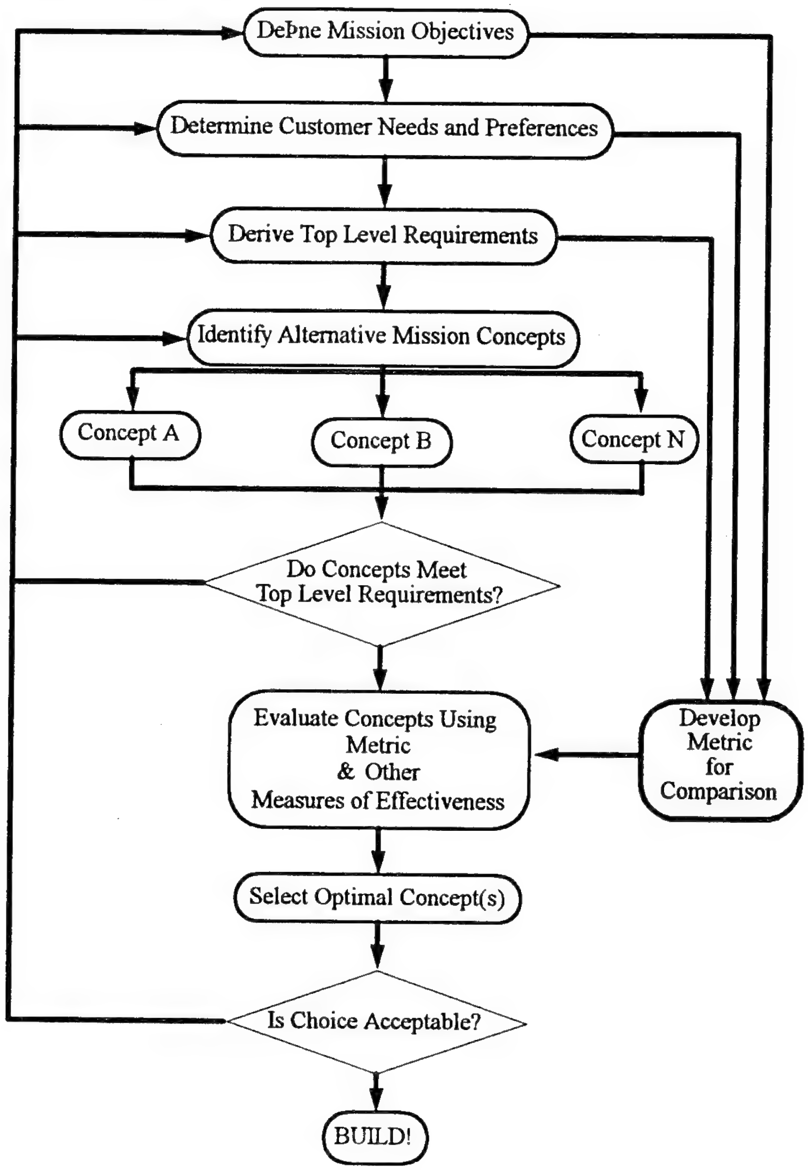

Figure 3-1 An Illustration of the Systems Engineering Process.

The flow of this process, although illustrated to demonstrate its use in the comparison of different systems architectures, can be applied at all levels of the design process. The main steps in the process are as follows.

3.1.1 Define Mission Objectives/Establish Program Philosophy

At the start of a new program, or in our case when beginning an evaluation of disparate systems, it is necessary to clearly define the objective(s) of the mission. At

this point in the process it is necessary to ask the question, "What do we want to achieve by this program?" The commercial company, in particular, will need to decide what product it plans to supply to a particular market. President Kennedy defined very clear objectives when he set the objective of the Apollo Project to put a man on the moon within the decade [Shea, 1992]. The statement was clear, and left little room for interpretation. Setting the objectives provides only one half of the equation, however.

Since the development of a complex system will inevitably involve choices throughout the design process, it is necessary to establish a set of ground rules which reflect program priorities and enable consistent decision making [Shea, 1992]. Systems design is a battle among performance, schedule and cost, so the program philosophy needs to reflect the relative importance of each element. The priorities set for the Apollo program, in order, were safety, schedule, cost and performance. Safety became the highest priority because the lives of the astronauts were on the line. Schedule followed as the next most important priority due to President Kennedy's clear constraint to reach the moon by the end of the decade. Cost and performance, although they were also important issues to consider to ensure the mission could be met within the budget, became secondary considerations.

The purpose of this thesis is to evaluate the effectiveness of various mobile satellite system architectures to address a limited market. Multiple companies have proposed to deploy satellite constellations in order to provide global, handheld voice communications to mobile users. The main objective of each system is inevitably to make money, since they have been proposed by commercial companies. The priorities set by a commercial system should be to provide a service that the consumer wants (a needed service at a level of performance to be determined), at a cost that the consumer is willing to pay, while still making a profit. Each system should therefore be evaluated on the basis of their major priorities of cost and performance.

3.1.2 Determine Customer Needs and Preferences

Before spending a great deal of money developing a system, a company must first determine whether there is a viable market for its services. If a viable market is found to exist, it becomes necessary to quantify the needs and preferences of the expected customers' so that they can be designed into the system. "The market appeal of a satellite Personal Communications System (PCS) will be based on its perceived value to the potential user community. A system's success will be based on its ability to strike an acceptable balance between the scope of the offered services and the cost that the user of those services is willing to bear" [Warwick, 1994].

Since understanding the target market is also necessary in order to complete a fair comparative evaluation of disparate systems, the first step of this study will be to determine the characteristics of the mobile satellite market. Analysis of market data, derived from both published sources and from representatives in the industry, will be presented, and the results of the analysis will attempt to define the market in both a qualitative and a quantitative sense. Consumer preferences, derived from the market analysis, will then be transformed, along with the mission objectives, into a set of measurable top level requirements.

3.1.3 Derive Top Level Requirements

Once the philosophy and objectives of the mission have been defined, and a market study has been conducted, it is necessary to transform the customer preferences, along with the mission objectives and program philosophy, into a solid set of top level requirements. The requirements must be clear and measurable, and should also be directly attributable to the mission objectives. Requirements will generally come in three forms [Larson & Wertz, 1992]:

Functional: How well must the system perform to meet mission objectives?

Operational: How will the system operate and interact with the users?

Constraints: Other limiting criteria that will affect the system design.

The resulting top level requirements provide a measure of whether the system design will adequately meet mission objectives. Since systems are designed to requirements, it is natural that they should also be evaluated by how well these requirements are met. Therefore, the next step in the thesis will involve the derivation of top level requirements from the market study, so that different system architectures may be evaluated.

3.1.4 Identify Systems to Evaluate

The systems designer is faced with alternative approaches at every step of the design process. "In the real world, there is no one unique approach to satisfying a set of requirements. There often exist a set of solutions which are 'pretty good', and a much larger set that are 'not so good' or worse. The design task is to separate the 'good' wheat from the 'bad' chaff [Shea, 1992]. It is important to remember that "no complex system can be optimum to all parties concerned" [Shea, 1992].

This study will attempt to address the orbital altitude debate in a rigorous way, by evaluating different mobile satellite system architectures within the framework of the systems engineering process. Although many systems have been proposed that could successfully satisfy the MSS market, system architectures based on the three licensed MSS systems (Iridium, Globalstar, Odyssey) and a fourth system based on a GEO design (Tritium) were selected for evaluation. A fifth system called *Iris*, based on a point design conducted by students in a graduate systems engineering class, was added to complete the architectures for evaluation [MITMobile, 1995]. Since detailed design information was not always available, and various aspects of each system were

estimated, the evaluation conducted in this study does not directly determine the effectiveness of the proposed systems. Instead, the proposed systems served as models for the architectures evaluated in the study. The model architectures evaluated in this study have been labeled as follows: LEO-66, LEO-48, MEO-12, MITMEO-12, GEO-3. Although the names indicate that many of the technical details for the modeled systems were derived from published data on the proposed systems, the results of the study cannot be considered a prediction of how well each of the proposed systems will perform. The available technical data on the proposed systems was sparse in many areas; often due to proprietary reasons since the companies are in an intense competition to get to market first.

3.1.5 Develop Metric for Comparison

As a system design progresses, many aspects of the design will be refined and modified. As design choices are identified throughout this process, it is necessary to evaluate how well each choice will affect the design of the system. Tradeoffs between different approaches will need to be made, and the resulting decisions should be made in the context of both the program philosophy and the top level requirements. It is therefore important to develop a quantitative approach to determine how well each design satisfies the top level requirements.

Wertz and Larson [1992] call this step of the process *mission analysis*, which involves quantifying "the system's performance and its ability to meet the ultimate mission objectives." They define two types of tools to quantify system performance:

1. *Performance parameters*: Quantify how well a system works, without explicitly measuring how well it meets mission objectives; and

2. *Measures of Effectiveness*, or *Figures of Merit*: Quantify directly how well the system meets mission objectives.

Although performance parameters can be useful measures of the system's performance, they are not as directly tied into the system's design, since they do not relate directly to the mission objectives. Good figures of merit, however, are considered critical to successful mission analysis, and should be [Larson & Wertz, 1992]:

1. Closely related to mission objectives;

2. Understandable by decision makers;

3. Quantifiable; and

4. Sensitive to system design (if used as a design selection criterion).

If possible, it is useful to define a single systems-level Figure of Merit to use as the primary measure to determine how effectively a design meets system objectives. This primary Figure of Merit, or metric, should provide a measure of how well the systems requirements are met, consistent with program priorities, and be sensitive to all major drivers of the system. At every stage in the design process, the effect of each choice on the overall design should be measured by the corresponding change in this metric.

4. Market Analysis

> *The market appeal of a sat PCS will be based on its perceived value to the potential user community. Crudely put, it is based on striking an acceptable balance between the scope of the services on offer, and the cost the user of those services is willing to bear [Warwick, 1994].*

When bringing a new product to market, it is important to carefully consider the needs and preferences of the customer. In order to be successful, the design of the system must be market-driven, and the designer must match the expected market to the available technology. A design that is not driven primarily by the market will likely be unprofitable, as the system will either fail to fulfill customer needs and preferences, or the system will be overdesigned. A commercial design that is driven primarily by technology instead of the market will be costly, and more than likely fail to deploy on time.

Having previously defined the methodology of the study, this chapter will present a market analysis overview which will include a market study. The chapter will identify the target market segments, and summarize the key product and service assumptions, and the sampling approach used in the study. Results of the study, including the expected number of addressable users, and user needs and preferences, will be described next. The last two sections of this chapter will describe the addressable market model derived from the market

study, and list the top level requirements derived from the results of the user preference survey.

4.1 Market Study

A good market study must determine the needs and preferences of the user population, so that they can be translated into a set of top level system requirements. In addition, it is necessary to determine both the size of the addressable population and the distribution of that population.

Most of the companies that have proposed systems to provide mobile satellite services have conducted market studies and surveys to determine specific customer preferences. Although most of the market study results were unavailable due to its proprietary nature, information was collected from a variety of sources, including: FCC reports, journal articles, and sources in the industry. Much of the market information was collected through guest lectures presented to a graduate space systems engineering class at the Massachusetts Institute of Technology in the spring of 1995. Lecturers included representatives from Comsat [Elizabeth Young & Edward Jurkiewicz], Communications of Clarksburg [Walter Morgan], Hughes Space and Communications [Jack Juraco], Inmarsat [Olof Lundberg], Orbital Sciences Corporation [Jan King], Qualcomm [Andrew Viterbi], Raytheon [Paul Babbitt, Arthur Curly, Bob Francois, Jack Schust], and TRW [Roger Rusch]. Although all of the lecturers did not specifically address market analysis, they each provided unique insights into customer needs and buying preferences.

4.1.1 Market Segments

Most of the proposed systems plan to address similar segments of the MSS voice communications market. The personal land mobile market for handheld and fixed in-vehicle services includes the following three market segments:

International Business Travelers (IBT): Users traveling internationally for business purposes to regions with either incompatible cellular standards or not cellular services at all. Business travelers from developing countries in Western Europe and North America traveling within their own region and 50% of those traveling within Eastern Europe were excluded.

National Roamers (NR): Users who roam from areas of cellular coverage into areas not covered by cellular services within a given country.

Cellular Extension (CE): Business users who are based in regions of a given country not covered by cellular services.

4.1.2 Key Product and Service Assumptions

Key product and service assumptions derived for the market studies include,

- Handheld voice service must be interoperable with the home region terrestrial cellular system, providing voice quality similar to current digital cellular services, and allowing medium penetration call announcement.

- Target price for the handheld phone will be less than $1500 US (production cost of around $500 US), with end-user charges of around two dollars (US) a minute.

- Handset will be sized at approximately 300 cubic centimeters, weigh around 300 grams, and utilize a 15 cm by 2 cm diameter helical antenna.

- Handset will provide radiated power of less than 0.5 Watts so that radiation emissions are well within the tighter standards being contemplated in many countries.

- Additional handheld characteristics include an equivalent isotropic radiated power (EIRP - transmitted RF power times transmitted gain) of -0.5 dBW, and a G/T (receiver gain divided by receiver system noise temperature) ratio of -25.5 dB/K.

- Handset will provide approximately one hour of talk time with an additional 24 hours of standby time.

4.1.3 Sampling Approach

KPMG (UK), Peat Marwick's advanced technologies unit (UK), and Harris Research (UK) conducted a detailed market research study of customer preferences that included 1125 face-to-face interviews conducted in ten countries. The countries, including the United States, Poland, Brazil, Korea, Mexico, Italy, Turkey, Britain, and Indonesia, were chosen to represent the world both geographically and economically, giving IBTs and NRs approximately equal weighting. A second, parallel study involved an in-depth simulation study with 200 business people to explore "user cooperation factors".

The market studies began with a "grossing-up", or filtering process that combines the interview results with other data to ensure that the addressable market model population has the same characteristics as the interview sample. The IBT market was grossed up by obtaining IBT travel pattern data from the World Travel Organization. In addition to company data provided by the respondents, grossing up of the national markets (both NR and CE) was based on external information such as company size, number of companies, and the proportion of blue collar to white collar workers. The data was extended globally (i.e. to other countries not included in the interview sample) by utilizing external econometric and demographic data from various sources such as the Gross Domestic Product (GDP), population, etc.

4.1.4 Addressable Market Size

In order to determine the size of the addressable market, it is necessary to consider the number of potential users willing to buy the service, the average utilization rate of each type of user, and the limiting effects of competition from terrestrial fixed and mobile communications.

The number of potential users was derived by using the grossing-up method previously discussed to extrapolate the number of worldwide users that were similar to interview sample. The resulting numbers were modified to consider competition from terrestrial fixed and mobile communications. The number of addressable minutes of service were derived by considering the utilization rate per subscriber based on the number of business trips, nights per trip, and calls per day away provided by each interviewee. Utilization rates for each market segment were estimated at about 650, 300, and 1500 annual minutes for IBTs, NRs, and CEs, respectively, resulting in an addressable market of around 2.8 B minutes of service in 2005.

4.1.5 Customer Preferences

The first set of interviews were conducted on two types of potential users: International Business Travelers (IBT) and National Roamers (NR). The participants were presented with the expected behavior of three different system architectures (LEO, MEO, & GEO), and were asked questions regarding their overall preferences, and to what extent they would be willing to cooperate to make the call. A latter study conducted an in-depth simulation of all three MSS architectures using a sample of 200 business travelers. This second study concentrated on different aspects of user cooperation, including: How far would users be willing to walk to make the call? How long would they be willing to wait? Would limited call durations be acceptable? The study also simulated the level of signal delay expected for each of the systems.

The following main conclusions were derived from the study:

1) If service can be provided at a relatively low cost, a viable market exists for high quality voice communications that is easily accessible to handheld terminals; and

2) Users were sensitive to relatively small changes in technical parameters which can change the apparent attractiveness of the space segment architectures considered.

A number of different factors affected consumer acceptance, including: equipment cost, cost of a call, signal delay, risk of call dropout, in-building availability, and the level of user cooperation necessary to complete a call. In general, it was found that the user cooperation, in-building availability, and call dropouts were the most important factors to the consumer, although signal delay and costs were considered important as well.

User Cooperation: Handheld communications will often require some level of user cooperation to complete the link (successfully connect a call between the user and a satellite). Users may need to move in order to connect a call to a GEO satellite, since the satellite is stationary with respect to the user. In contrast, since non-GEO satellites are moving, the user may need to wait until a satellite comes into view before successfully placing a call [Young, 1994]. The study found that users would be willing to wait up to five minutes to connect a call, and would be willing to move up to 100 yards to place a call. When given a choice between the two options, however, both the IBTs and the NR's were split evenly on the issue. In other words, half of the users would rather walk to a clear area to place a call, while the other half would rather wait for a satellite to come into view.

Risk of Dropped Calls: The risk of a dropped call was the next most important issue. The risk is a function of the duration of a call, the quality of the connection, and the dynamics of the viewing geometry. An average call length of five minutes was assumed for the IBTs (four minutes average call length for Inmarsat). When simulating call dropouts in the market study, LEO-based

systems came out the weakest due to their lower elevation angles, faster transit times, and fewer simultaneous satellites in view.

In-Building Availability: All the systems were found to be limited in this area. GEO systems can provide limited use inside if the user has line-of-sight (LOS) to the satellite when in front of a south-facing window (north-facing if in the southern hemisphere), while non-GEO systems could also provide limited LOS service in front of a window, although the user may be required to wait for a satellite to come into view. In general for MSS, only paging capability is considered practical for reception inside buildings and in dense urban areas where line-of-sight is not available [Dorfman, 1993]. Since terrestrial fixed and mobile communications have the advantage in non-LOS conditions such as within a building, it is expected that they will handle most of the urban traffic.

Price Sensitivity: It was found that service price was less important than the terminal price in terms of market penetration. The terminal price was assumed to be less than $1500 US. The IBTs were assumed to use the service for thirty days out of the year, while the NRs averaged around 18 days of service per year. As displayed in Figure 4-1, the effect of increasing the price per minute of service on the user usage rates (toll charge elasticity) was found to vary little between $2 and $3 per minute, although the difference between $1 and $2 per minute appears significant.

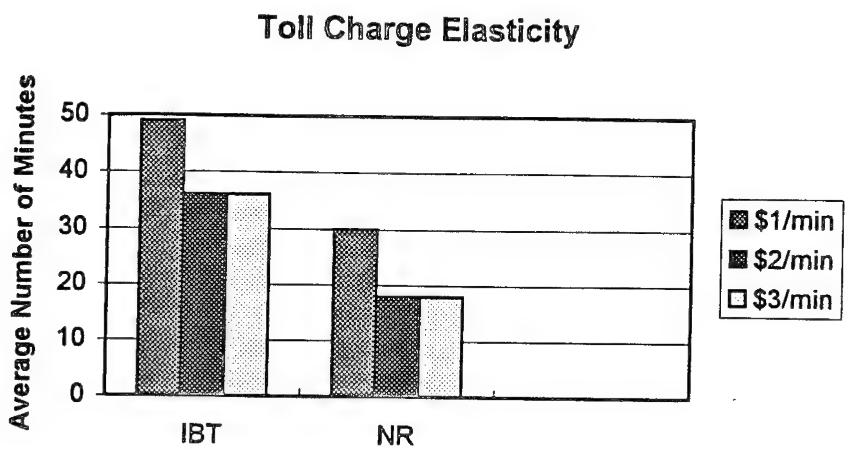

Figure 4-1 Toll Charge Elasticity

Signal Delay: All 200 users in the simulation study were requested to listen to simulated signal delay levels. It was found that with effective echo canceling techniques, signal delay was considered the least important factor to the users. However, it was also found that 18% fewer travelers would use a GEO-based system than a non-GEO system due to signal delay effects.

4.2 Addressable Market Model

Given an addressable market size of 2.8 B minutes of service in 2005, it was necessary to distribute that market geographically. This distribution was accomplished by assuming that the majority of traffic will come from areas not currently covered by cellular networks, with additional traffic from IBTs traveling in regions with incompatible cellular standards. Based on the results of the study and this approach, the addressable market distribution expected in 2005 was developed as depicted in Figure 4-2.

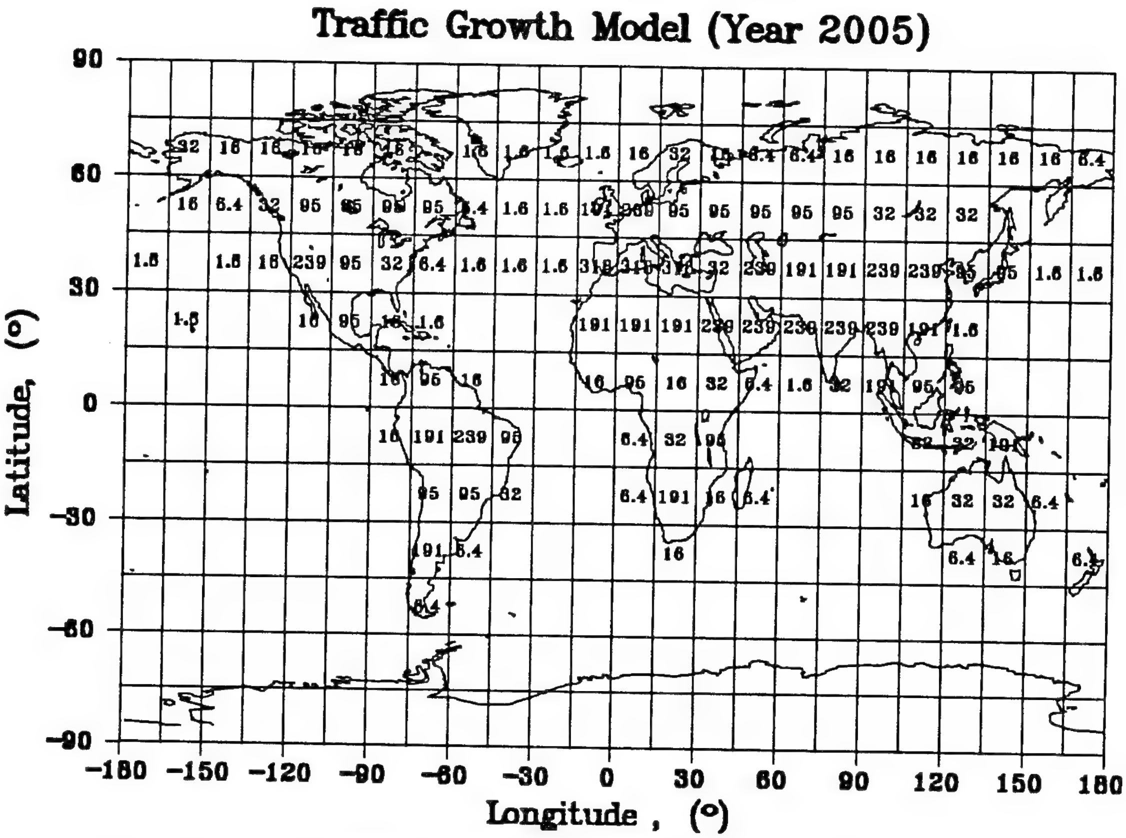

Figure 4-2 **Addressable Market Distribution in 2005, in Millions of Minutes per Year.**

The map is divided into 15° Latitude by 15° Longitude grids, where the number in each grid represents the number of potential minutes of service (in millions of minutes) expected from that grid during the year. There are eight different levels of user activity depicted in the figure, not including the blank grids that are assumed to have negligible traffic.

In order to estimate the yearly revenue expected from each of the modeled systems, the expected traffic map in 2005 must be extrapolated over the full 12 years of the system lifetime. This study assumes a 4.5 year take-up half life (i.e. the market reaches half of its expected growth in 4.5 years, and peaks 4.5 years later). The resulting growth curve for 100% of the addressable market is represented in the following figure. Since this study evaluates how well each

system can satisfy a limited-growth market, curves representing 10% and 31% market penetration are included.

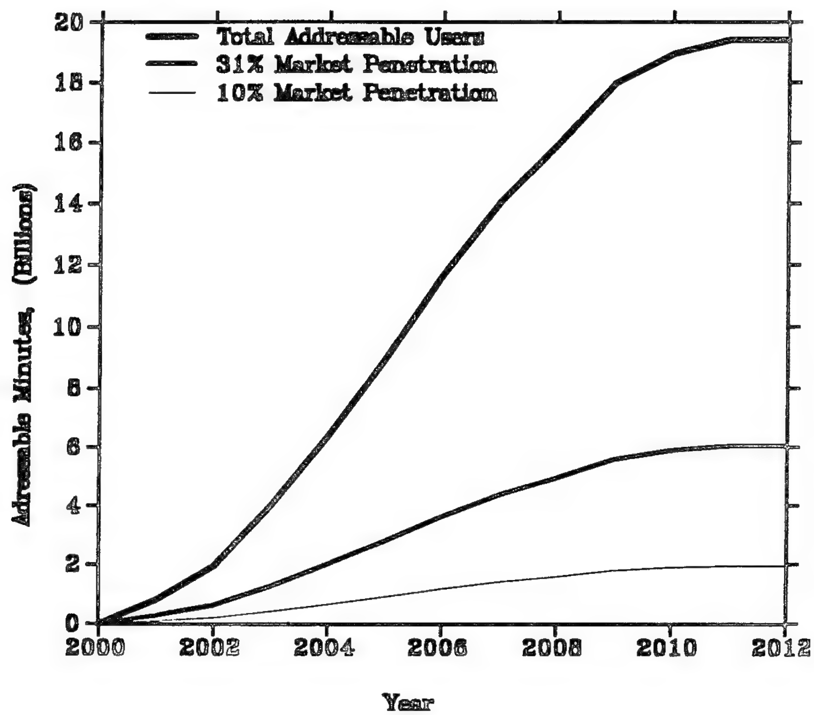

Figure 4-3 Addressable Market Growth (Millions of Minutes per Year)

Due to regional differences, and the penetration of terrestrial communications, each traffic grid is not expected to grow equally. In fact, it is expected that traffic in developed nations will grow little, and reach a limit, as cellular and other terrestrial services will be expected to eat away at the market share. The peak growth areas are expected to be in China, the Russian Federation, parts of Africa, and South America.

The overall growth curve depicted in Figure 4-4 was distributed geographically amongst the grids by considering these issues. In order to simulate the limiting effect of competition in high traffic areas, each grid was limited to a maximum of 125 millions of minutes per year. As the growth rate was applied to the traffic model in each successive year, all of the non-limited grids were increased until

the total traffic matched the total market growth displayed in Figure 4-3. Figure 4-4 illustrates how each of the eight traffic levels grow to maintain the total market growth. The eight numbers listed in the legend represent the eight traffic levels expected in 2005, expressed as the number of addressable minutes per year. The addressable market maps for every year from 2001 to 2012 are listed in Appendix A.

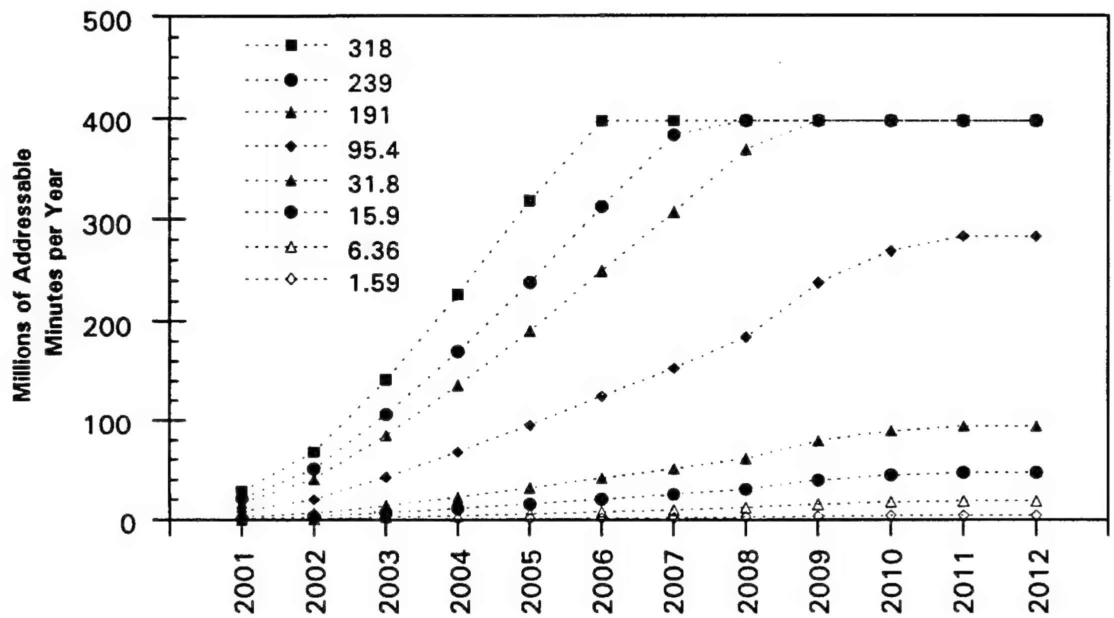

Figure 4-4 **Regional Traffic Growth for the Eight Traffic Levels Estimated for 2005, in millions of minutes per year.**

4.3 Top Level Requirements

The results of the customer preference studies were translated into a set of top level requirements, against which each of the modeled systems will be evaluated and compared.

- The primary service shall be voice transmission with a voice datarate of 4800 bits per second (bps) provided at a bit error rate (BER) of 10^{-3} (1 bit error out of every 1000).

- Each system shall be fully operational by Jan 1, 2001.
- The system lifetime shall be 12 years from the initial operating condition (IOC) in the year 2000.
- The system shall be compatible with the PSTN and with regional cellular networks.
- The system shall provide global service meeting the requirements set forth by the Federal Communications Commission.
- The system shall satisfy all applicable ITU, FCC, and regional PTT regulations
- The handsets shall meet all health and safety standards set by ANSI and IEEE.

5. MSS Communication Basics

The purpose of this chapter is to provide the reader with a brief introduction to aspects of mobile satellite communications. It will begin with an introduction to the mobile communications link, and a summary of its geometry. The majority of the chapter will concern an introduction to the fundamental link equation, a mathematical expression describing the power lost in a communications link between two antennas, and a discussion of the quality of the communications link. The chapter will close with an overview of two other aspects of communications particularly important for mobile satellite systems: multiple access techniques, which provide a means to satisfy multiple users within the same communications medium; and power control. Throughout the chapter, details of both the proposed and modeled systems will be provided, and assumptions made in this study will be highlighted.

5.1 Communications Link

Figure 5-1 illustrates an example of a full duplex communications link for a typical mobile satellite system. The signal path from the mobile customer to the other party is commonly referred to as the return link (*returning from* the customer), while the forward link (*forward to* the customer) represents the signal

path back to the customer. The customer's voice, modulated onto an RF carrier, will travel up to the satellite covering the region (return uplink), and down to the nearest gateway antenna (return downlink), where the signal can be routed to the other party through either the public switched telephone network (PSTN) or another path. The return signal will travel back to the customer in the same manner (forward uplink to satellite, forward downlink to user). If the satellite above the mobile user does not have an available gateway antenna in view, as portrayed in the figure, the signal can be routed through a nearby satellite (crosslink) that has a gateway connection. Systems that do not utilize satellite crosslinks will be unable to complete the connection in this situation.

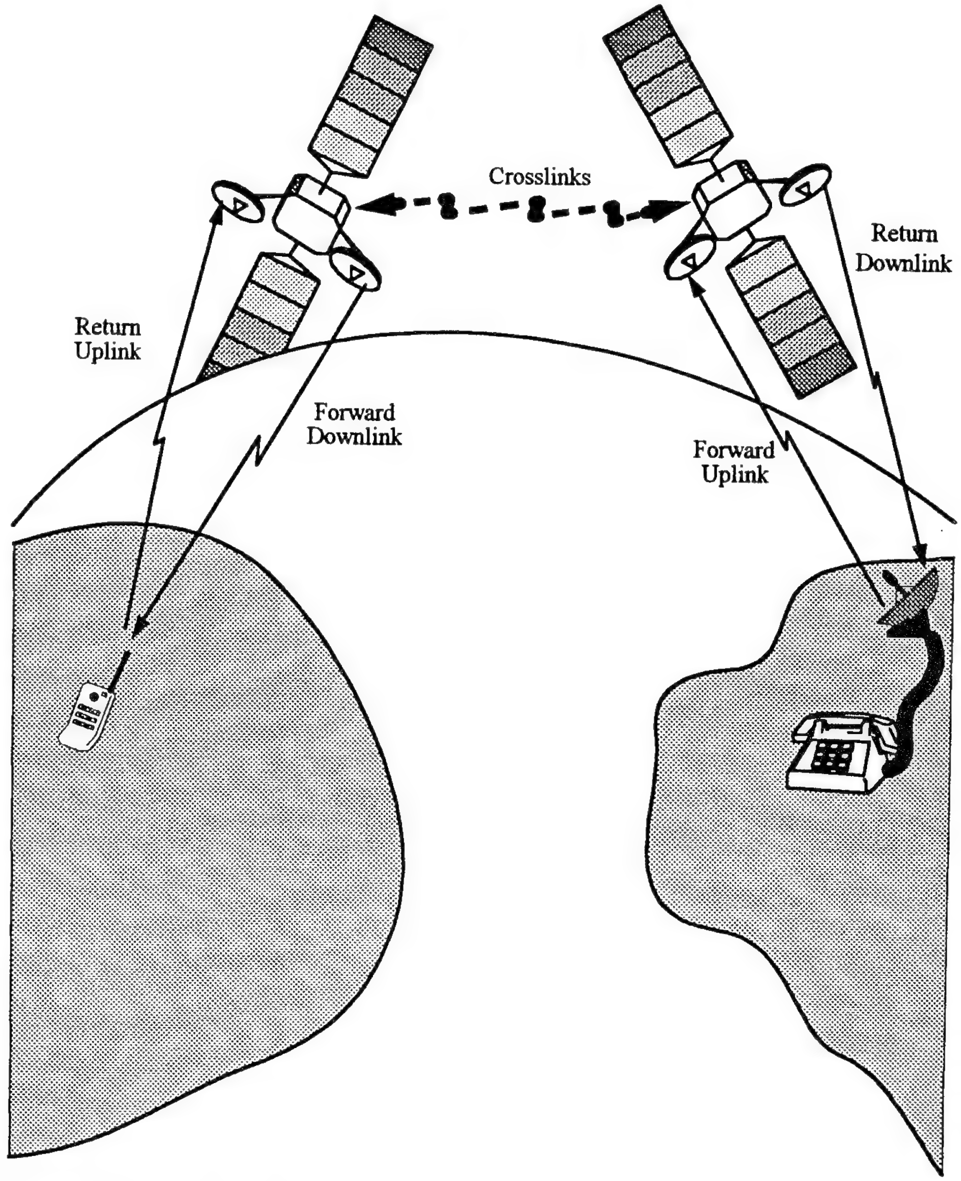

Figure 5-1 **Example of a Communications Link for a Mobile Satellite System**

5.2 Link Geometry

Since any discussion of a communications link between two antennas is highly dependent on the geometry of the situation, it is useful to define the geometry of the satellite-based communications link. The visibility of the satellite to both the mobile user and the gateway antenna is a function of the satellite's elevation angle. Figure 5-2 represents the satellite viewing geometry that defines the

relationships between the satellite and a random point on the Earth's surface, such as a ground station. The orbital altitude and the radius of the Earth are indicated by h, and R_E, respectively. The angle between the subsatellite point, and the target on the Earth, as measured from the satellite is called the *nadir angle*, η. The *Earth central angle*, λ, is also an angle between the subsatellite point and the target, but measured from the center of the Earth. The *elevation angle*, ε, measured from the target, is the angle to the satellite above the local horizon [Wertz & Larson, 1992].

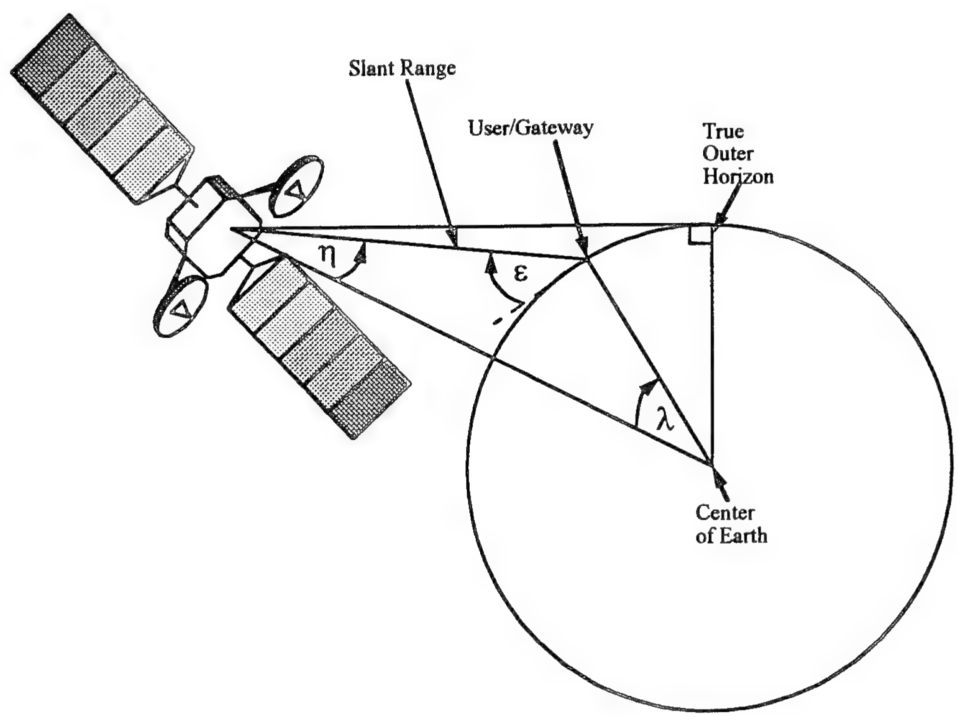

Figure 5-2 Geometry of the Communications Link

The elevation angle, the central angle, and the satellite altitude are related by the fundamental equation:

$$\cos(\lambda + \varepsilon) = \frac{\cos(\varepsilon)}{1 + h/R_E}$$

(5-1)

The elevation angle is an important parameter in satellite communications since it is directly related to the slant range distance between the satellite and the target. The slant range distance to a target, R_{slant}, directly relates to the signal delay, and to many losses causing degradation to the communications link. It can be calculated given the elevation angle, the central angle, and the satellite altitude:

$$R_{SLANT} = (h + R_E)\frac{\sin(\lambda)}{\sin(90 + \varepsilon)}$$

(5-2)

5.3 Fundamental Link Equation

When the user speaks into the mobile phone handset, a voice activated chip in the handheld unit (vocoder) samples the input waveform to create a digital representation of the user's voice, and compresses the resulting information stream to reduce the amount of data to be transmitted. Forward error correction techniques (see section 5.4) are applied to the digital stream, if necessary, and the signal is then modulated onto an RF carrier, amplified, and transmitted to the servicing satellite. The power of the RF signal will be degraded on the way to the satellite due to interference, spatial spreading, atmospheric attenuation, and variations in the signal strength due to obstructions in the propagation path. The satellite receiver detects the weak incoming signal from the antenna, shifts the waveform to the downlink carrier frequency, amplifies the signal, and retransmits it down to the gateway.

In order to describe the dynamics of the communications link, it is necessary to relate all of the relevant parameters that affect the link in a mathematical

expression. The customary representation of these relationships is referred to as the *fundamental link equation*. Many sources provide detailed derivations of this expression, and the discussion that follows summarizes information found in multiple sources [Pritchard, 1993; Ippolito, 1992; Gordan, 1993; Lovell, 1995; Davies, 1992; Martin, 1978].

If a signal is transmitted from an antenna equally in all directions (isotropic antenna), the power received at a receiver, R meters away from the transmitter, can be represented by the following equation:

$$P_r = \frac{\eta A_r}{4\pi R^2} P_t \tag{5-3}$$

where η is the efficiency of the transmitting antenna, P_t is the transmitted power, A_r is the area of the receiving antenna, and $4\pi R^2$ represents the area of a sphere of radius R. Most antennas do not radiate equally in all directions, but are designed to focus the signal in a particular direction. If the transmitting antenna is able to focus the signal towards the receiving antenna, then the signal will arrive at the receiving antenna at a higher power level. This resulting gain is often expressed by a ratio between the power received by the actual antenna in a given direction and the power that would have been received if the antenna had been transmitting equally in all directions. If both the transmitting and receiving antennas are able to focus their sensitivity towards each other, the power arriving at the receiving antenna can be expressed by multiplying the gain of the transmitting antenna by equation (5-3),

$$P_r = \frac{A_r G_t}{4\pi R^2} P_t \tag{5-4}$$

where the efficiency has been incorporated into the antenna gain ratio. This equation can be rewritten in a different form by utilizing the *universal antenna formula* [Pritchard, 1993]:

$$A_r = \frac{G_r \lambda^2}{4\pi} \tag{5-5}$$

This equation relates the effective area of the receiving antenna with the gain of the receiving antenna. When incorporated with equation (5-3), the formula for the received power becomes:

$$P_r = \frac{P_t G_t}{4\pi R^2}\left(\frac{G_r \lambda^2}{4\pi}\right) \tag{5-6}$$

where λ is the wavelength of the signal which can be calculated by dividing the speed of light by the signal frequency. This expression can be rewritten as:

$$P_r = P_t G_t G_r L_s \tag{5-7}$$

where L_s represents the free space loss,

$$L_s = \left(\frac{\lambda}{4\pi R}\right)^2 \tag{5-8}$$

which is a term that includes the loss due to spatial spreading of the signal $(4\pi R)^{-2}$ and the signal wavelength, λ. (NOTE: Many sources define the free space loss as the inverse of the above expression.) Many other losses in addition to the signal spreading will contribute to the degradation of the signal strength

along the way to the receiver, and can be multiplied in a chain next to the space loss,

$$P_r = P_t G_t G_r L_s L_1 L_2 \ldots L_n$$

(5-9)

where each of the n loss terms are expressed as a fraction. The additional link losses used in this study include *circuit losses*, L_c, due to inefficiencies in the path from the transmitter to the antenna; *propagation losses*, L_p, due to atmospheric and rain attenuation; and *fading and blockage losses*, L_f, due to attenuation, depolarization, and multipath interference caused by obstacles in the transmission path. The latter two loss terms will be further discussed later in this chapter.

The received power expression alone does not adequately describe the signal in terms of how well it can be understood at the receiver. What really needs to be described is the relationship between the received signal power and any noise observed by the receiver. This relationship is generally expressed as the carrier signal (C) to noise (N) ratio, which represents the information-carrying capacity of the communications link:

$$\frac{C}{N} = \frac{P_t G_t G_r L_s L_c L_p L_f}{N}$$

(5-10)

Many factors can contribute to the noise experienced by a receiver. One of the main sources of receiver noise, commonly referred to as thermal noise, is caused by the motion of the electrons in the receiver itself. The thermal noise of an object is a function of the object's temperature, so the noise caused by the receiver within a range of frequencies, Δf, can be expressed as:

$$N = kT_{sys}\Delta f$$

(5-11)

where k represents Boltzmann's constant in watt-seconds/°K, and T_{sys} represents the system temperature. Since the receiving antenna will receive thermal noise emitted from all objects within its field of view, engineers combine all of these effects into the system temperature, which represents the equivalent noise temperature of the receiver. Other factors in addition to passive thermal noise can also add to the total noise experienced by the receiver. One effect that can be especially important in the mobile link is the noise power received due to interference from other sources, I_o (in watt-seconds). When these expressions are combined with equation (5-10), the signal-to-noise ratio becomes:

$$\frac{C}{N} = \frac{P_t G_t G_r L_s L_c L_p L_f}{M\left(kT_{sys} + I_o\right)\Delta f}$$

(5-12)

where M accounts for any power margin required to insure against individual losses.

Since most current communications systems now utilize digital modulation techniques to transmit information, it is sometimes more convenient to express the signal-to-noise ratio in terms of the energy received per bit of information, E_b. The energy received per bit of information can be written as $E_b = C/R_{data}$, where R_{data} represents the datarate, or the number of bits received per second. The digital equivalent of the signal-to-noise ratio is written in terms of a ratio between the energy-per-bit received to the noise density (the noise received per Hz, i.e. $N_o=N/\Delta f$),

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r L_s L_c L_p L_f}{\left(kT_{sys} + I_o\right) R_{data} M}$$

(5-13)

The fundamental link equation for satellite-based digital communications can be rewritten as follows:

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r L_c L_p L_f \lambda^2}{16\pi^2 \left(kT_{sys} + I_o\right) R R_{slant}^2}$$

(5-14)

where the free-space loss has been expressed by equation (5-8), and R_{slant} represents the slant range distance between the satellite and ground antennas. This equation for E_b/N_o can be used to describe any one of the links (forward-uplink, return downlink, etc.) by selecting the appropriate variable values.

Multiple link calculations, such as combining the gateway to satellite and the satellite to user links (forward link), can be calculated by combining the budget for each individual link in the chain as follows:

$$\frac{1}{\left(E_b/N_o\right)_{received}} = \frac{1}{\left(E_b/N_o\right)_{gateway}} + \frac{1}{\left(E_b/N_o\right)_{user}}$$

(5-15)

If one of the links in the equation, such as the gateway-to-satellite link, is designed to provide a large E_b/N_o ratio, its contribution to the overall E_b/N_o ratio may be considered negligible. This is commonly referred to as "buying the link", since the systems designer can spend more money on the design of one segment of the link to reduce the required size, power and complexity of another segment. The assumption is made in this study that each individual mobile satellite system will "buy" the gateway link, and hence it will be considered negligible in all the link calculations that follow.

Now that the link equation has been introduced, the next few sections will discuss some of the handheld, and payload link loss assumptions used in the link calculations.

5.3.1 Handheld Unit Assumptions

The design of the handheld unit is a major driving factor in the design of a mobile satellite system. The designer must consider that both the satellites and the users may be in motion, and hence the line of sight between the users and the satellites will be constantly changing. Since one cannot expect the user to track the satellites with the mobile phone as they are both in motion, handheld antenna must operate over a wide (nearly hemispherical) field of view.

If the systems utilize handheld terminals with true hemispherical antennas, the expected gain of the terminal is a ratio of the power received by a target antenna divided by the power that would be received by the target antenna if the handheld terminal radiated equally in all directions:

$$G = \frac{P_t / \left(2\pi R^2\right)}{P_t / \left(4\pi R^2\right)} = 2 \cong 3dB \tag{5-16}$$

Most of the proposed systems have listed handheld gains between 1 and 3 dB, although a conservative handheld gain of zero dB (no gain) has been assumed for the purposes of this study since there is considerable uncertainty in the community as to how the close proximity of the head will affect the effective gain. Indeed, modeling by Jensen et al has shown that "the tissues absorb between 53% and 68% of the power delivered to the antenna for a head-handset separation of 2 cm" [Jensen, 1995].

Since the handheld gain must be low to operate in the MSS environment, the next obvious variable is the handset's transmitted power. Since the user wants a

small, handheld terminal with a relatively long battery life that operates within current ANSI and IEEE safety guidelines, the average handset power must also be kept low. The maximum, time-averaged transmitted power from the handset can be represented as:

$$P_{\max_{avg}} = P_{peak} V_a \tag{5-17}$$

where P_{peak} is the max power transmitted by the handset, and V_a is a fractional value representing the percentage of time that people actually talk during a telephone conversation. Modern cellular handsets are designed to be activated whenever a person speaks, and remain in a standby (i.e. non-transmitting) mode during lulls in the conversation. Since most telephone conversations are silent during 60% of the call [Morgan & Gordan, 1989], a voice activity factor of 0.4 was assumed. Since most of the proposed systems plan to keep their time-averaged transmitted power from the handset low, a maximum, time-averaged transmitted power level of 0.5 watts was assumed for the link calculations. When combined with equation (5-14), the link equation becomes

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r L_c L_p L_f \lambda^2}{16\pi^2 V_a \left(kT_{sys} + I_o\right) R R_{slant}^2} \tag{5-18}$$

5.3.2 Satellite Payload Assumptions

Since the systems that are being compared in this study are partly modeled after some of the proposed systems, extensive design data was obtained from open literature, speakers at MIT, and from representatives in the industry. However, since many of the design details are considered proprietary due to the highly competitive nature of the industry, many of the estimates were instead based on relationships with known parameters.

The maximum radiofrequency (RF) power transmitted from each satellite represents one of the more important variables in the simulation that needed to be estimated. Since there are some definite relationships between the satellite dry mass, power, and payload power, it is possible to estimate the maximum RF power available. The following relationships, or industry *rules-of-thumb,* were presented by Professor Robert Lovell during a graduate class in Space Systems Engineering, taught at MIT in the Spring of 1995. Professor Lovell spent 25 years with NASA and 8 years in industry. As Director of NASA's Advanced Research and Development Program in Satellite Communications, he directed the International Satellite Aided Search and Rescue Program, the Advanced Communications Technology Satellite Program, and the Mobile Communications Satellite Program, while at Orbital Sciences Corporation he directed the development of mobile satellite systems such as Orbcomm. The following rules-of-thumb represent his experience in mobile communications in industry, and at NASA [Lovell, 1995].

- Communications payload takes up 33% of the satellite's dry mass, M_{dry}.
- Payload power to mass ratio of 6 watts/kg.
- One feed element per beam.
- L- and S-band receivers consume 1 watt each.
- ASICS (Applications Specific Integrated Circuits) digital signal processing (DSP) electronics consume 5 watts each and weigh 1 kg per element.
- DC to RF power conversion efficiency, ε_{DCtoRF}, of 20%.

If a system utilizes onboard processing (i.e. the payload provides onboard demultiplexing, demodulation, decoding, routing, formatting, encoding,

modulation, and retransmission to the ground), the maximum RF power for system can be estimated as follows:

$$P_{RF} = \left[\left(\frac{M_{dry} - (1kg)N_B}{3} \right)(6W / kg) - (1W / receiver)N_B - (5W / element)N_B \right] \varepsilon_{DCtoRF}$$

(5-19)

where N_B is the number of spotbeams. If the communications payload instead operates as a simple bent pipe (i.e. the uplink signal is merely received, converted to the downlink frequency, amplified, and then retransmitted), the equation can be simplified by excluding the rules of thumb relating to onboard DSP.

$$P_{RF} = \left[\left(\frac{M_{dry}}{3} \right)(6W / kg) - (1W / receiver)N_B \right] \varepsilon_{DCtoRF}$$

(5-20)

Gumbert has shown the utility of these simple relationships [Gumbert, 1995].

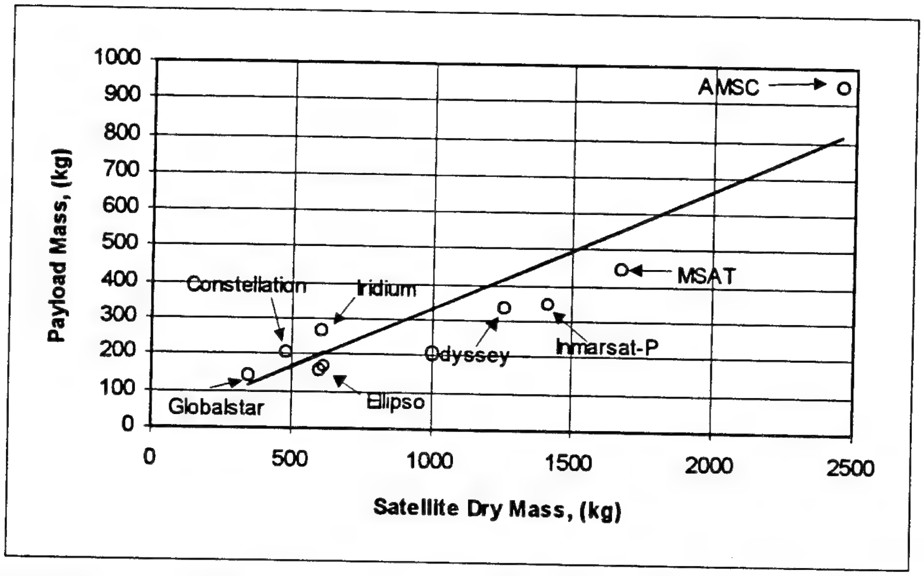

Figure 5-3 Comparison of Rule-of-Thumb Payload Mass Estimates with Published Values for Proposed Mobile Satellite Systems.

Figure 5-3 shows the relationship between satellite dry mass and payload mass, plotted against the published values for many of the proposed MSS.

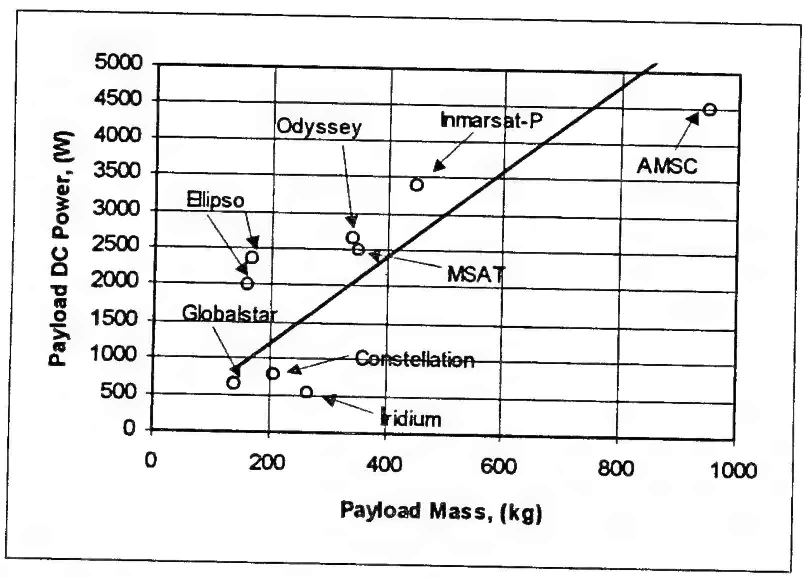

Figure 5-4 Comparison of Rule-of-Thumb Payload DC Power Estimates with Published Values for Proposed Mobile Satellite Systems.

Figure 5-4 displays a similar comparison of the relationship between payload mass and payload power versus the published data. These figures show a

reasonably good fit with the published values and will provide a rough estimate for the model architectures that is generally consistent with the proposed systems. The following table presents the published data from the proposed systems [from their refiling with the FCC in Nov. 1994], along with the associated rule-of-thumb estimates for the model architectures.

Table 5-1 Rule-of-Thumb Estimates of Satellite RF Power for the Modeled Systems

SATELLITE CHARACTERISTICS	Iridium	Globalstar	Odyssey	Iris	Tritium
Onboard Processing?	YES	NO	NO	NO	NO
Number of Spotbeams	48	16	37	48	160
Spacecraft Dry Mass (kgm)	607	349	1254	1212	2812
MODELED ESTIMATES	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
Payload Mass (kgm)	202	116	418	404	937
Payload Power (W)	927	698	2507	2424	5625
Satellite RF Power (W)	128	136	494	474	1093

Other aspects of the system designs, including antenna gains, spotbeam patterns, and frequencies, are included in Appendix B as part of the simulation control files.

5.3.3 Losses in the Communications Link

5.3.3.1 *Propagation Losses*

Propagation losses of -1 dB, in both directions, were assumed for each of the systems to account for degradations of the mobile link due to atmospheric and rain attenuation, and tropospheric scintillation. Degradation calculations, based on models published by Crane [Crane, 1979], were calculated for each of the MSS architectures for a variety of conditions. The sum of all the propagation losses were on the order of -1 dB.

5.3.3.2 *Fading and Multipath Losses*

Most fixed satellite systems enjoy clear line-of-sight communications between the satellites and the mobile stations. Although rain attenuation can become a

problem when operating at high frequencies (>10 GHz), space losses are generally the dominant concern for fixed satellite systems. Mobile satellite system handheld terminals, however, will not often experience clear line-of-sight communications with the satellite system.

Obstructions *shadowing* the terminal (within the line-of-sight) can cause fading (variations in the amplitude and phase) or complete blockage of the signal. In addition, near-isotropic mobile antennas in some environments can experience severe fading due to *multipath* (signals reflected off of the ground or other obstacles). A fixed terminal with a highly focused antenna pattern is generally immune from this *multipath* fading; however, the wide, nearly isotropic antenna characteristics of the handheld terminal will receive multiple, time-offset reflections of their own incoming signal that can constructively, or destructively, add with the original signal. Figure 5-5 depicts the situation for a land mobile channel.

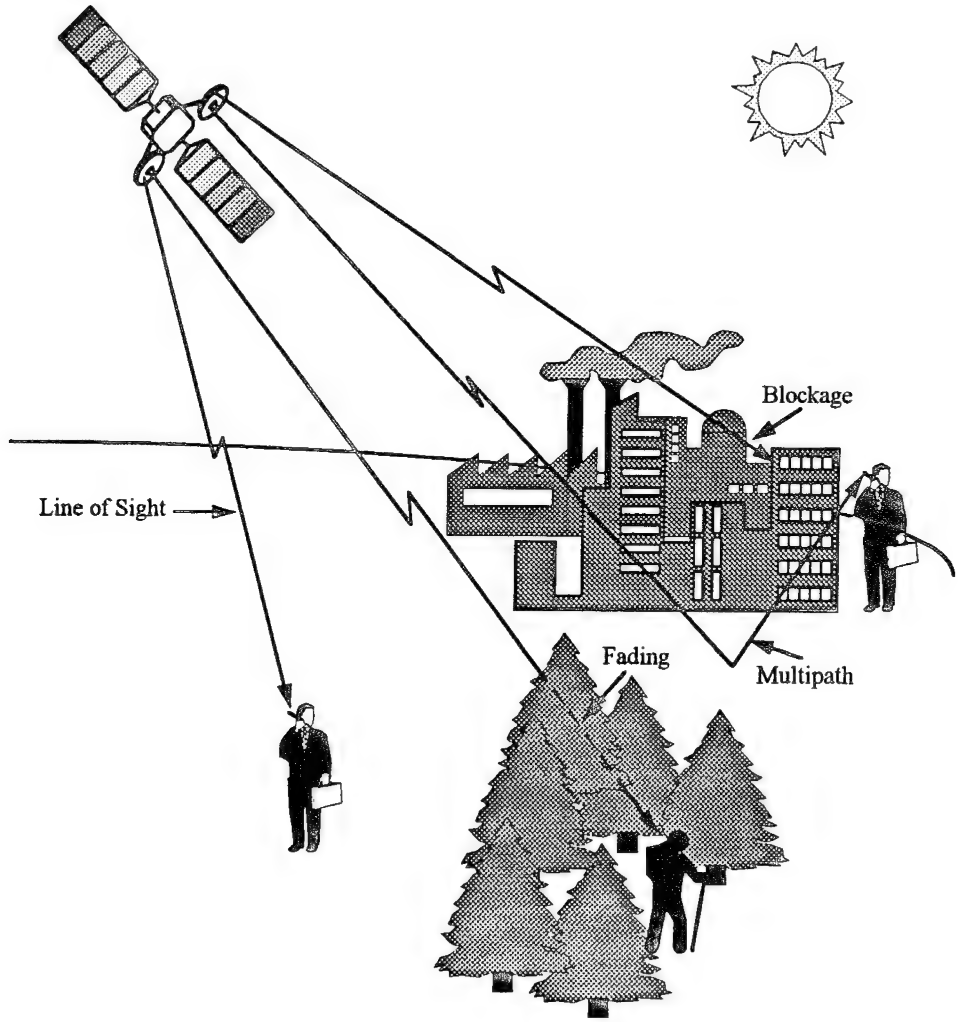

Figure 5-5 **Fading and Multipath Propagation Experienced in the Mobile Communications Channel.**

The amount of blockage and multipath experienced by a mobile system will vary significantly with the elevation angle between the terminal and satellite antennas. As the elevation angle becomes smaller, the amount of shadowing experienced and the probability of a signal being blocked will increase. These effects will also vary considerably with the mobile user's environment. A user standing in a wide open field will experience very little shadowing (until extremely low elevation angles are experienced), but will experience some multipath reflections of the signal off ground. The urban user will experience severe blockage and multipath effects due to tall buildings, while the user in a

tree-shadowed environment will suffer attenuation and absorption of the signal from foliage, and blockage from branches and trees. The suburban user will observe a combination of effects from buildings, trees, and other obstructions. These effects also vary significantly with the season, the frequency of the signal, and with movement of the mobile terminal.

Many authors have taken L- and/or S-band propagation measurements in a variety of urban, suburban, and tree-shadowed environments [Devieux, 1993; Goldhirsh, 1990; Sforza, 1993; Stutzman; Matsudo, 1993]. Since both the satellite and mobile antennas are in motion, the level of fading and multipath experienced takes on a probability distribution. Most of the fading measurements published present the expected losses as a function of both the elevation angle and the probability that the link will be available (unblocked) for a given link margin.

Data has been taken most extensively in the tree-shadowed, roadside environment, as this environment is considered the dominant factor for land-mobile systems [Vogel & Goldhirsh, 1990; 1989; Lutz, 1991; Barts], and a widely-used model for this environment has been developed [Goldhirsh & Vogel, 1992, Sforza, 1993]. Unfortunately, a large portion of the users will be in different environments. For the purposes of this study, the typical subscriber distribution was approximated to be spread in a combination of 10% urban, 40% rural, and 50% suburban environments [Young, 1995]. It is very difficult to generalize all of the reported results in order to estimate the maximum and average fading levels expected in each of these environments. Vogel has stated that there may be an empirical model available in the next year to provide that information [Vogel, 1995]. In the absence of a general model applicable to all environments, it was necessary to come up with a simple model to estimate these parameters. Data presented by Smith, Gardiner and Barton [Smith, 1993] provides suggested margins for a variety of environments.

Table 5-2 **Suggested Margins vs. Link Availability for L and S-Band Mobile Satellite Communication Channels [Smith, 1993].**

Environment	Link Availability (%)	Margin (dB) L-Band, Elevation Angle (°) 40	60	80	Margin (dB) S-Band, Elevation Angle (°) 40	60	80
URBAN	99	13.1	10.7	8.1	17.3	15.4	13
	95	8.2	5.9	1.3	12.5	11	6.7
	90	5.5	3.8	0.9	10.1	8.7	4.3
	85	4.5	3.1	0.9	8.7	7.4	3.2
	80	4	2.7	0.8	7.6	6.3	2.7
	70	3.4	2.4	0.7	5.8	4.8	2.4
SUBURBAN	99	7.2	4.4	2.2	12.5	10.8	9.2
	95	4.5	2.5	1.4	6.7	6	6.3
	90	3.5	1.9	1.1	5.1	4.5	5.2
	85	3	1.7	1	4.4	3.9	4.7
	80	2.7	1.6	0.9	3.9	3.5	4.2
	70	2.3	1.4	0.8	3.3	3	3.6
TREE SHADOWED	99	11.3	7.7	4.1	12.6	10.5	9
	95	7.9	4.9	2	6.3	5.7	5.2
	90	5.9	3.4	1.5	4.7	4.2	3.8
	85	4.8	2.8	1.4	4	3.6	3.2
	80	4	2.5	1.3	3.6	3.3	2.8
	70	3.3	2.2	1.2	3.1	2.8	2.5

Efforts to fit the Smith data with a reasonable function were not very successful. Due to a lack of sufficient modeling data for average fading conditions that applied over all three environments, a simplified model was developed for L-Band fading, based loosely on the data presented in Table 5-2 and data provided in the previous references [MITMobile, 1995]. A similar model for S-Band data was not modeled from the Smith data since the reported fading levels did not follow expected trends. Typical maximum L-Band fade margins required for users in urban, suburban and rural environments were estimated with the following equation:

$$F\left(P_{avail},\varepsilon\right) = a_1 + \left(a_2 P_{avail} - a_3\right) Ln\left(\tfrac{\pi}{\varepsilon}\right) \tag{5-21}$$

where P_{avail} is the probability that the link will be available (expressed as a percentage), ε is the elevation angle, F is the resulting maximum fade (in dB) that would be experienced by the mobile L-Band channel, and a_i are the environment-dependent coefficients:

Table 5-3 Coefficients for Fading Estimate

Environment	Urban	Suburban	Rural
a_1	0.6	0.6	0.6
a_2	0.46	0.18	0.15
a_3	34.3	12.8	11.5

These relationships between maximum L-band fade levels for a given availability, as a function of elevation angle, are plotted in the following figure.

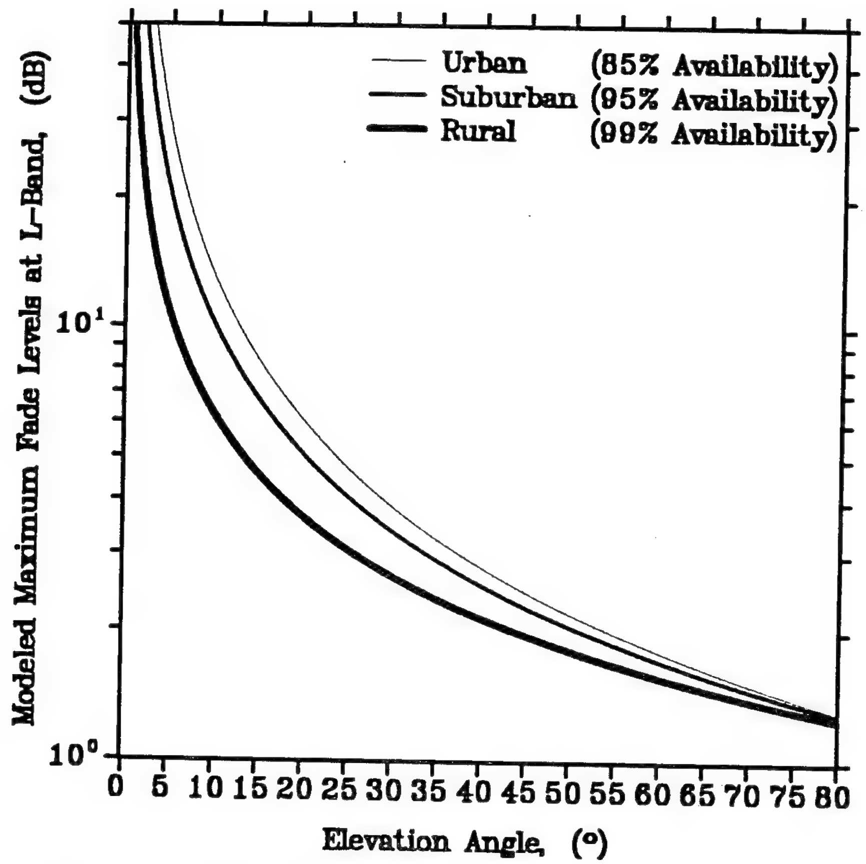

Figure 5-6 Simplified Fading Model

These simple relationships defined the so-called *average-maximum* fading conditions. Since it is unduly conservative to require each system to always provide the maximum fading margin to close the link, *average-average* fading levels, estimated at half of the *average-maximum* levels, were utilized in the calculations. Since it has been shown [Goldhirsh & Vogel, 1992] that the ratio of fading levels are "approximately consistent with the ratio of the square root of

the frequencies," the S-Band fading levels were estimated from the L-Band levels with the following relationship,

$$F_S = F_L \sqrt{\frac{f_S}{f_L}}$$

(5-22)

where F_S and F_L are the maximum fading levels, and f_S and f_L are the frequencies for S-Band and L-Band.

These fading values were then combined to determine a weighted, average fading value for all of the environments,

$$F_{avg} = \mu_{urban} F_{urban} + \mu_{suburban} F_{suburban} + \mu_{rural} F_{rural}$$

(5-23)

where μ represents the average customer distribution in urban (10%), suburban/tree-shadowed (50%), and rural (40%) environments.

5.4 Link Performance

The performance of digital signals is often measured as the bit error rate (BER), a number that describes the probability that a individual bit in the data stream is received incorrectly. For example, a communications link operating at a BER of 10^{-3} will receive an average of one incorrect bit out of every 10^3 bits in the data stream. For a given modulation technique, there is a relationship between the E_b/N_o ratio required to achieve a particular BER.

Information can be modulated onto a carrier frequency by varying the amplitude, frequency, or phase of the carrier voltage. The voltage of the carrier, V, at time t, can be represented as follows:

$$V[t_i] = A_c \sin(2\pi f_c + \theta_c)$$

(5-24)

where A is the amplitude of the signal, f_c is the carrier frequency, and θ_c is the phase of the signal. Most of the proposed systems are utilizing one form or another of phase modulation. One popular modulation scheme utilized in many of the proposed mobile systems is Quadrature Phase Shift Keying (QPSK), which transmits digital data information (shift keying) by varying the phase between four (quadrature) distinct values (or more accurately, 4 ranges of phase). This concept is depicted in the following figure.

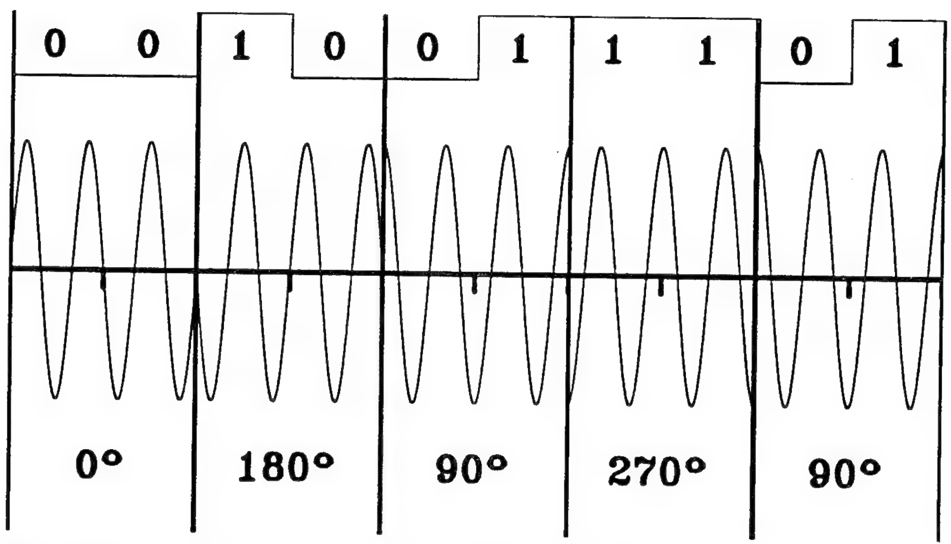

Figure 5-7 An illustration of QPSK modulation.

The efficiency of transmitting accurate data varies with each form of modulation, and can be represented by a relationship between the E_b/N_o ratio required to achieve a required BER. This relationship is displayed in Figure 5-8 for different forms of modulation.

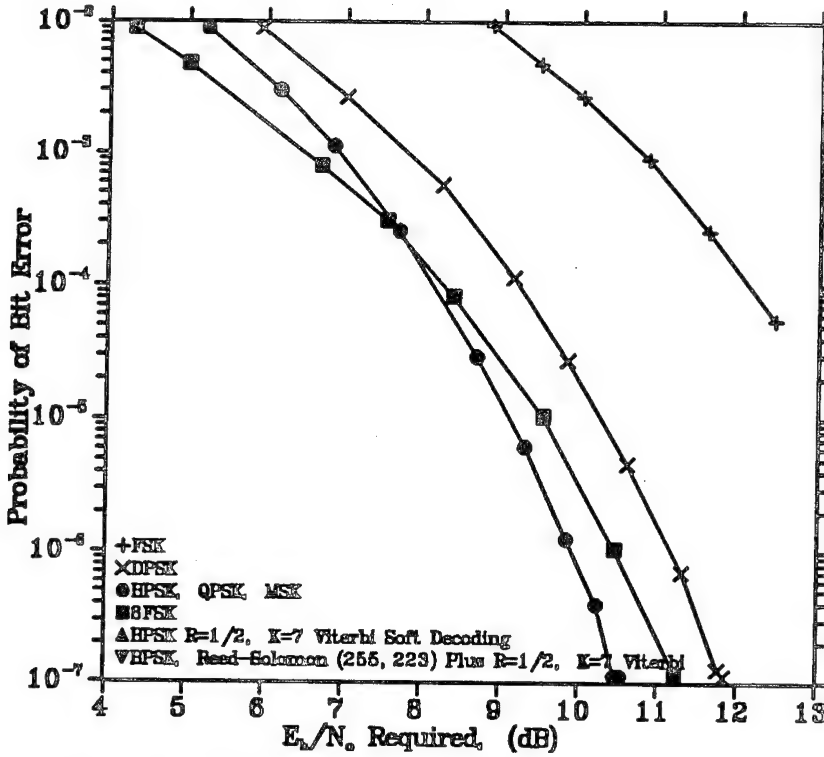

Figure 5-8 E_b/N_o vs BER relationships [Davies, 1992].

It is clear from Figure 5-8 that some modulation schemes can achieve a given BER with less received power, and hence less transmitted power, per bit of information. Two approaches can be taken if the link designer needs to further improve the link performance achievable with a given modulation scheme (i.e. increasing the link quality for given bit rate, or increasing the bit rate for given quality) [CCIR, 1985]:

1) *Increase the signal-to-noise ratio:* This can be achieved by improving either the Earth station equipment or the satellite by providing more power, larger antennas, and/or lower system temperatures; or

2) *Reduce the required E_b/N_o:* By utilizing corrective coding techniques, such as forward error correction (FEC), it is possible to trade an increase in bandwidth for a reduction of the E_b/N_o required to achieve a given BER.

The best choice for a mobile satellite system is clearly to reduce the E_b/N_o required by utilizing corrective coding since the mobile terminals need to be small (in size, weight and power), and since both satellite and launch costs scale directly with the satellite mass and power.

Corrective coding is a scheme by which additional information is added to the datastream such that the "uniqueness of a given message is accentuated, thereby allowing better discrimination against erroneous messages resulting from noise and interference" [CCIR, 1985]. By including redundant information in the datastream, the receiving terminal can detect the existence of errors and correct a portion of them, thereby lowering the BER. Although a detailed discussion of coding techniques is well beyond the scope of this thesis, a brief summary is in order.

When erroneous bits are detected at the receiver end of the link, some methods of error correction involve a retransmission of the faulty information. This method is not adequate for satellite-based voice communications, due to the time delay. Forward error correction is a method that does not require the retransmission of erroneous bits of data. Instead, FEC methods correct erroneous bits as they are detected, based on the redundant data included in the datastream.

FEC codes come in two basic flavors: block codes, and tree codes (convolutional codes are a common form of tree codes). Block coding techniques operate on blocks of data, which are then sent on to the modulator, while convolutional codes operate on the data continuously. Both types of coding techniques are used extensively in satellite communications. FEC codes are generally described by their code rate and their constraint length. The code rate is defined as the number of data bits (encoded voice information) sent in the datastream, divided by the total number of symbol bits transmitted. Thus, a rate 1/2 (R 1/2) FEC

code translates every data bit into two coded bits (symbols). The constraint length, or code length, K, is the length of the data stream on which the coding algorithm operates. The use of FEC increases the required bandwidth by 1/R, so a voice communications channel would require twice the bandwidth it would otherwise need. Figure 5-9 displays the relationship between required E_b/No and BER for different modulation schemes utilizing error corrective coding.

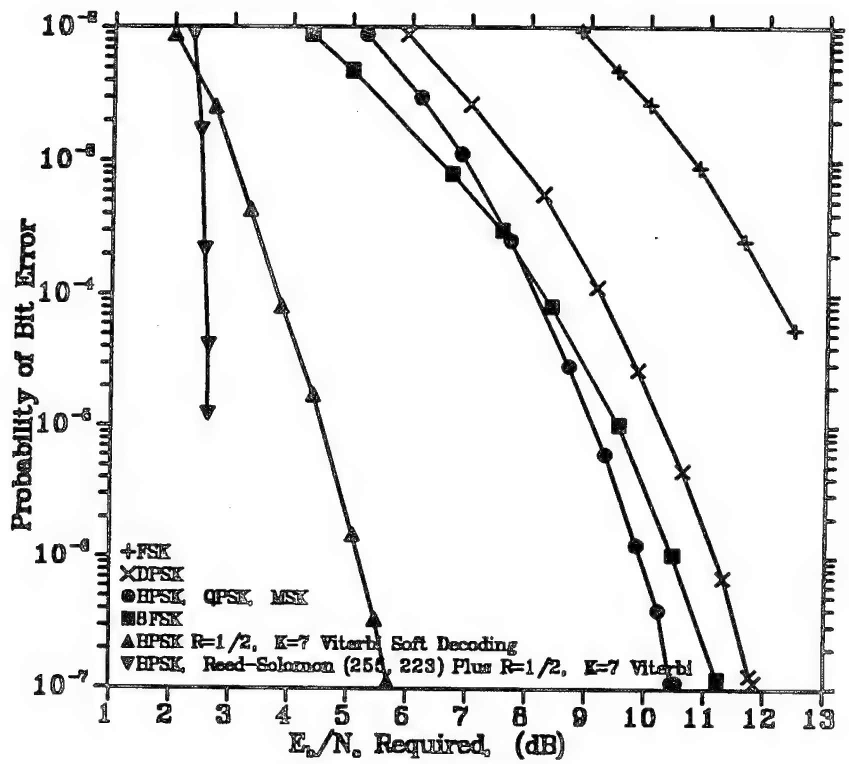

Figure 5-9 Relationship Between BER and Required E_b/N_o Ratio for Different Modulation and FEC Schemes [Davies, 1992].

5.5 Multiple Access Techniques

The purpose of a global communications system is to provide services to multiple users widely dispersed around the world. In order to satisfy multiple users, it is necessary to design the system to allow customers *multiple access* to the system's communications capacity. With the limited spectrum currently allocated for MSS (~16 MHz), it is especially important to find an efficient

method to provide multiple access in the available spectrum. Multiple access can be achieved by segmenting the available spectrum in the spatial, time, and/or frequency domains.

5.5.1 Space Division Multiple Access (SDMA)

Spatial separation between multiple users is one method to allow multiple access to the same spectrum, and can be achieved in a number of different ways. Multiple access can be provided at the system level by providing separate satellites to multiple users. On the individual satellite level, multiple access can be provided through the use of multiple spotbeams. Spotbeams focus RF energy onto an area smaller than the satellites view area. By utilizing multiple spotbeams, the satellite is able to reuse the same spotbeams in non-adjacent beams.

Another method of spatial segmentation involves modulating multiple signals with orthogonal polarization. An RF signal consists of time varying electric and magnetic fields traveling away from the transmitter in a particular direction. Either field can be described as a combination of its three orthogonal components [Agrawal, 1986]:

$$\vec{E} = E_x\hat{x} + E_y\hat{y} + E_z\hat{z} \tag{5-25}$$

where the $\hat{z}$ direction can be described as the direction of propagation. An individual signal can be polarized by varying only one component of the signal. A signal is said to be horizontally polarized if E_x is zero, and vertically polarized if E_y is zero. Neither horizontal nor vertical polarization can be used in mobile communications, since the mobile antennas will not remain in a fixed orientation with respect to the EM fields [Lovell, Lecture Notes - Antennas, 1995].

Circularly polarized waves can be created by varying both the x and y components of the signal in a sinusoidal manner:

$$\vec{E} = E_o Sin\left(wt + \frac{\pi}{2}\right)\hat{x} + E_o Sin(wt)\hat{y} \qquad \text{(RHCP)} \tag{5-26}$$

$$\vec{E} = E_o Sin(wt)\hat{x} + E_o Sin\left(wt + \frac{\pi}{2}\right)\hat{y} \qquad \text{(LHCP)} \tag{5-27}$$

If both right (RHCP) and left hand circularly polarized (LHCP) waves (or horizontal and vertical) are used within a single beam, it is possible to transmit two signals within the same time and frequency space, without interference. This is possible since the signals are orthoganally polarized, meaning that the signals propagate in separate components of the field and do not affect each other.

Although the use of dual circular polarization on the mobile link could theoretically double the effective capacity of a system, it "does not appear to be a viable option for Mobile Satellite Service communications, since depolarization due to obstacles in the vicinity of the line-of-sight reduces the isolation" between dual-polarized signals "to unacceptable levels" [Vogel, Goldhirsh, and Hase, 1992]. It may be possible, however, to utilize dual polarization on the feeder links to reduce feeder link spectrum requirements.

5.5.2 Frequency Division Multiple Access (FDMA)

Frequency Division Multiple Access allows multiple users to be addressed in the same area and time by apportioning the available frequency spectrum into multiple channels. In order to prevent interference between adjacent bandwidth channels, it is necessary to allocate a small range of unused frequencies, referred to as guard bands, between the channels.

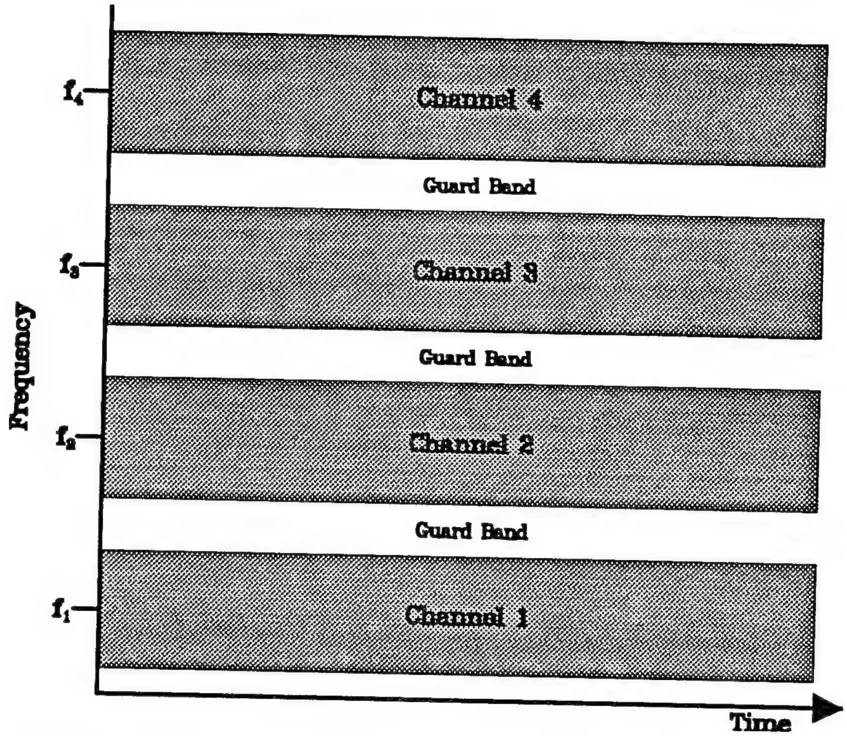

Figure 5-10 An Illustration of Frequency Division Multiple Access (FDMA)

5.5.3 Time Division Multiple Access (TDMA)

Instead of separating channels into separate frequency bands, they can be separated instead by segmenting the time domain. By transmitting at a much higher datarate than is necessary, each user can be assigned a unique time slot. As the mobile user's voice is digitally encoded, individual segments of the datastream can be transmitted at certain intervals at a much higher *burst rate.* TDMA makes multiple access possible because the system takes turns listening, and speaking, to each user. By segmenting user channels in time, the signals can be transmitted with little interference. Similarly to FDMA, TDMA requires guard bands in time between individual channels to avoid interchannel interference.

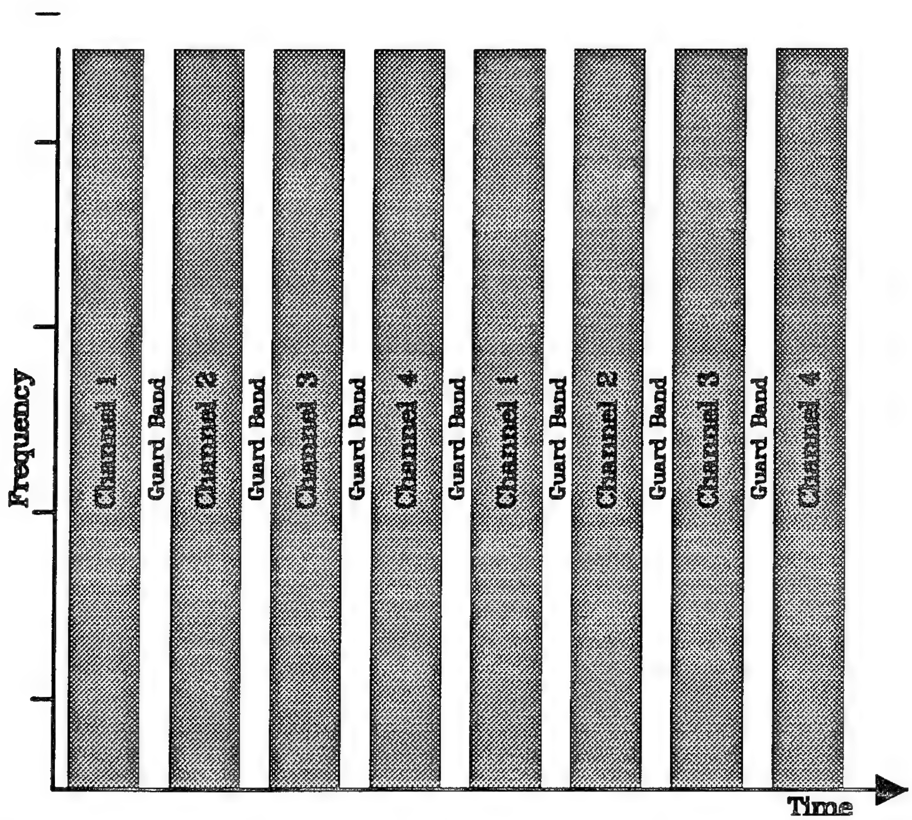

Figure 5-11 An Illustration of Time Division Multiple Access (TDMA)

5.5.4 Code Division Multiple Access (CDMA)

Although the previous methods have shown how multiple users can be addressed simultaneously through the apportionment of frequency, space and time, it is also possible to transmit multiple signals in the same frequency, time and spatial domains. By assigning a unique code to each user, it is possible to distinguish the individual signals at the receiver. In order to reduce the interference between separate users, the signals are modulated with a pseudorandom (PN) noise code, much faster than the datarate. Because the chip rate (PN code rate) is much faster than the datarate, the signal is spread over the full available bandwidth.

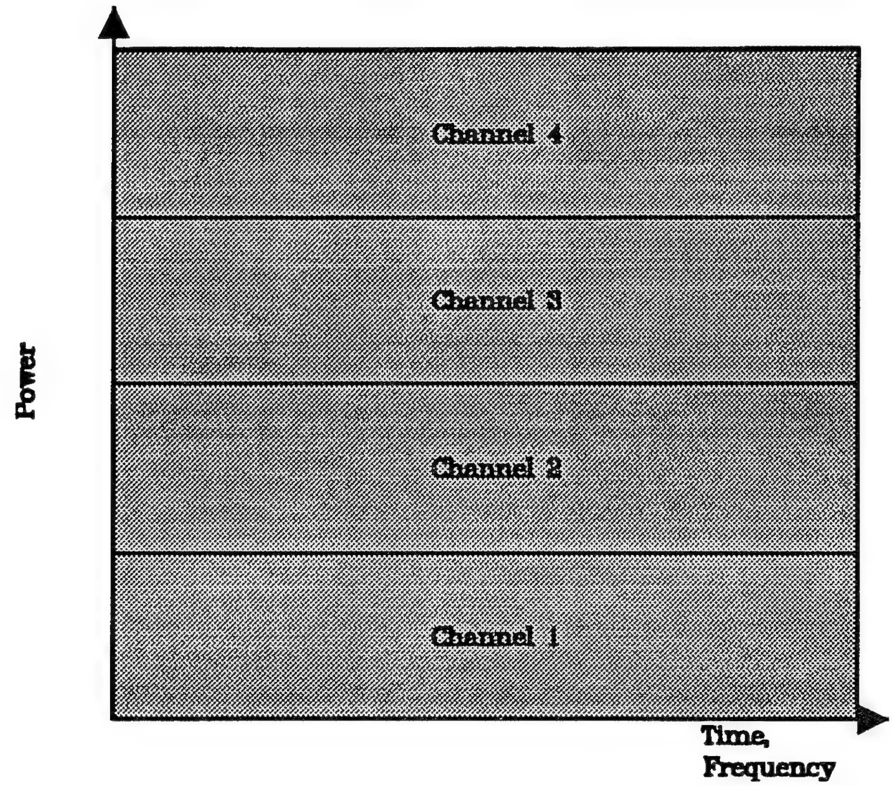

Figure 5-12 An Illustration of Code Division Multiple Access (CDMA)

A particular signal can be distinguished from all of the other signals, provided that the receiver is using the same code as the transmitter, and the codes are orthogonal to each other (two codes x and y are said to be orthogonal if their cross-correlation $\frac{1}{n}\sum_{i=1}^{n} x_i y_i$ is zero). All of the other users will appear as noise because the codes are pseudorandom. A pseudorandom code exhibits the property that its autocorrelation $\frac{1}{n}\sum_{i=1}^{n} x_i x_{i+j}$ is equal to one if the code is aligned [j=0], and zero otherwise [Hollister, 1994].

Each of the proposed systems, and hence our modeled ones, plan to utilize a combination of the previous multiple access techniques. Table 5-4 lists each proposed system, along with their chosen methods of multiple access.

Table 5-4 **Multiple Access Techniques for the Proposed Systems**

Proposed System	SDMA	FDMA	TDMA	CDMA
Iridium	48 spotbeams	yes	yes	yes
Globalstar	16 spotbeams	yes	no	no
Odyssey	37 spotbeams	yes	no	no
Iris	48 spotbeams	yes	no	no
Tritium	160+ spotbeams	yes	no	no

In addition to channelizing the available bandwidth into multiple frequency channels, Iridium plans to segment each frequency channel into four separate uplink and downlink channels, and assign each channel a time slice. This form of TDMA, where both links are combined into one frequency channel, is called Time Division Duplex (TDD). The method is illustrated in the following figure.

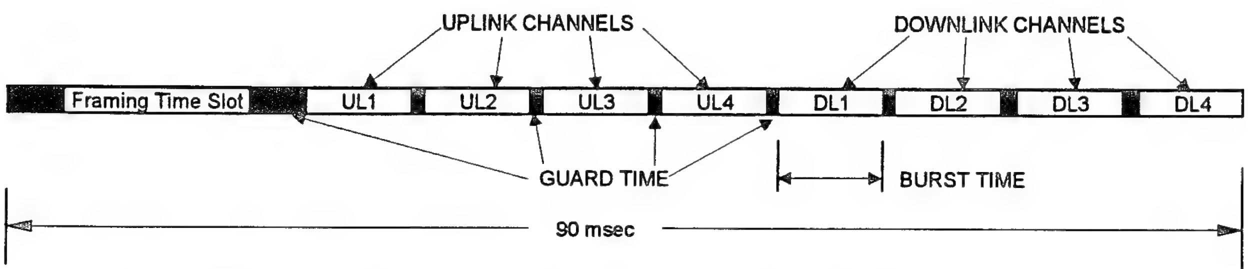

Figure 5-13 **An Illustration of Iridium's TDD/TDMA Frame Format [Motorola, 1992].**

All of the other proposed systems will utilize channelized CDMA, which involves separating the available spectrum into separate frequency channels (FDMA), and utilizing CDMA within each channel.

5.6 Power Control

The signal received in either direction of the mobile link will vary significantly due to the mobility of the satellites and the users. The capacity of a CDMA channel (See section 6.3) will be optimized when each transmitted signal is received at the same incoming power level [Viterbi, 1995; Viterbi, 1979]. Since a single user operating at a higher power level will act as a jammer, significantly reducing the overall channel capacity, it is necessary to control the variation of

each user's transmitted power level. In addition to the mobile uplink, control of the satellite's downlink power is necessary since it is a limited resource. This control of the transmitted power levels is difficult for the mobile channel since propagation, fading, and blockage effects will vary significantly as both the satellites and the users move.

One method to provide power control for a mobile satellite system, proposed for the Globalstar system [Monte, 1994], provides power control for both the forward and return links. In order to preserve satellite power, while still providing adequate signal quality to the individual user, the handset terminal will periodically measure the BER of the incoming signal. If the quality of the link becomes weak, the handset will send a message through the satellite to the gateway, requesting an increase in transmitted power. On the return link, it is the incoming E_b/N_o received at the gateway from each user that is controlled through both closed-loop and open-loop means, in order to minimize capacity degradation. As the gateway notices an increase in power received from an individual user, it sends a message to the terminal to reduce its transmitted power. This closed-loop control is meant to set the average signal level. In order to deal with faster signal variations caused by moving past obstacles (fast fades), an open-loop control method must also be utilized. When the handset notices that the signal from the gateway is getting weak, it's transmitted power is increased, under the assumption that there is a relationship between L and S-Band fading statistics.

Power control is considered difficult to implement for a satellite-based mobile voice communications system. In order to ensure that voice communications make it from the handsets to the gateway antennas, the various systems have designed a transmitted power margin into their return link calculations. This fade margin, M_f, has been included in the fundamental link equation:

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r L_c L_p L_f M_f \lambda^2}{16\pi^2 \left(kT_{sys} + I_o\right) R R_{slant}^2}$$

(5-28)

Since all of the excess power that is received at the gateway from this margin will appear as noise and degrade the link, the various systems will attempt to minimize this margin, and track the required power levels as closely as possible. This study has assumed that the various model systems will be able to power control to within 2 dBW (i.e. M_f=2 dB) [Rusch, 1995].

Now that a brief introduction of mobile communications has been presented, the next chapter will discuss the details of calculating the billable minutes for each system.

6. System Capacity

6.1 Introduction

The design of a worldwide communications system involves the optimization of a large number of design variables. One of the key aspects in the design process for communication satellites involves the evaluation of effective system capacity. Effective system capacity will be a function of many variables, including traffic demand, spotbeam coverage patterns, and various aspects of the satellite design. Traditional satellite communications have been performed from geostationary orbit, where the satellite, and its resultant beam pattern on the Earth, remain stationary. Accordingly, traditional models used in the industry to evaluate effective system capacity are designed to allocate system resources to maximize the number of addressable circuits, within system constraints, as user activity changes [Wernimont, 1989]. The method can be extended to evaluate the system capacity for a nongeostationary-based communications system, although the model becomes more complicated due to the dynamic nature of the satellite constellation.

Imagine a single duplex voice connection of predetermined quality between two mobile users. If the users are utilizing a geostationary system, such as Tritium, the physical path of the voice "circuit" will remain the same, with the occasional shift between adjacent spotbeams, or satellites, due to either the relatively slow

movement of the mobile users, or to active controlling of the system resources. If instead the two users are using a nongeostationary system, such as Globalstar, the physical path of the actual connection will be in constant flux as the signal is switched between spotbeams, satellites, and ground stations, and routed through the public switched telephone network. In addition to slow user movement, and the variations in traffic demand due to user activity, the nongeostationary system exhibits dynamic changes in relative distance between the satellites, users and feeder links. The dynamics of the nongeostationary orbits also further complicate the determination of an effective, or billable, channel. In a geostationary-based system, a circuit is considered a billable channel if the waiting user has a line of sight connection with an individual satellite spotbeam, and the satellite is physically able to establish the channel within certain constraints. Since their coverage areas remain fixed with respect to the Earth, each spotbeam on the GEO satellite can be optimized to address the expected traffic demand. Due to the motion of each nongeostationary satellite, spotbeam coverage areas for systems like Globalstar, are constantly changing, and the capacity of some individual spotbeams may be wasted covering low traffic demand areas in the oceans and at high latitudes. The evaluation of effective system capacities must therefore consider several factors to determine the usability of a potential voice circuit. Some of the more obvious factors to address include limiting the system capacity to the traffic demand, ensuring the satellite has line of sight with both the user and an available gateway antenna, and verifying the satellite has sufficient power and bandwidth to close the link.

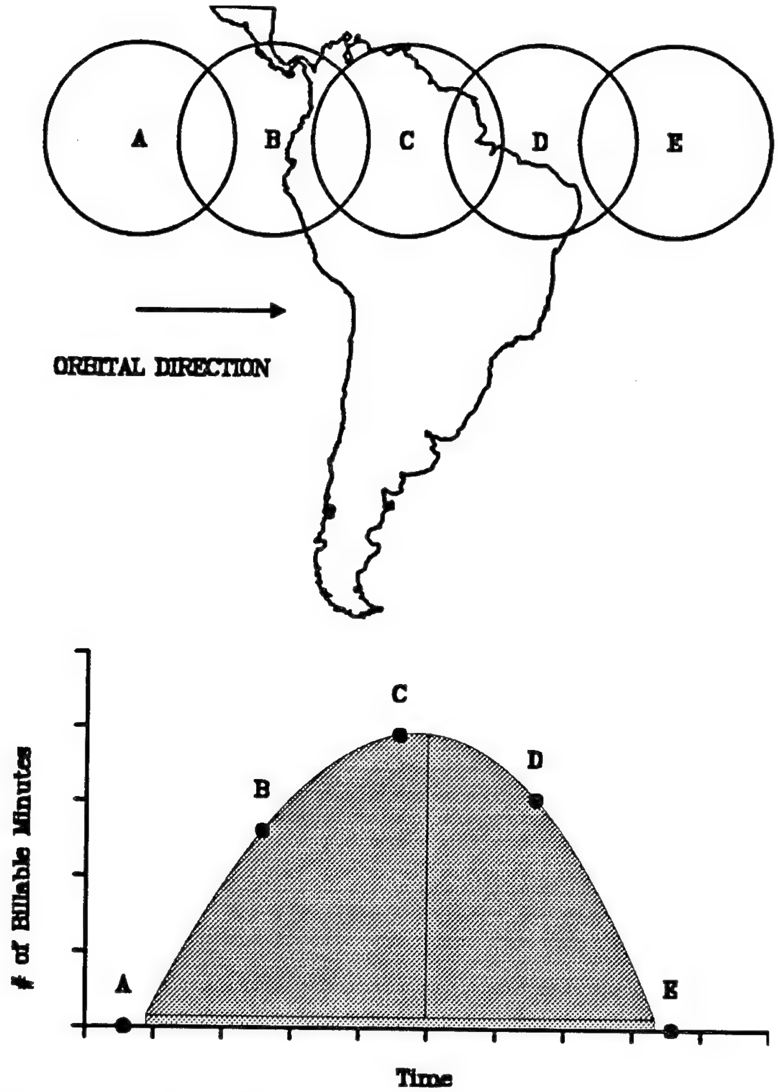

Figure 6-1 **An Illustration of Variable Capacity in a Nongeostationary Mobile Satellite System.**

Figure 6-1 represents the dynamics of a nongeostationary mobile satellite system with a simulated time history of an individual satellite's addressed capacity. When the satellite is located above position A, its effective channel capacity is very small due to the lack of user demand in the oceans. In other words, the satellite is severely market limited. As the satellite moves over position B, a portion of the satellite's view area intersects South America, and the satellite may be able to satisfy a limited number of users. The satellite's addressed capacity may still be market limited at this point, or it may be hitting constraints

within individual spotbeams. The number of addressed channels increases when the satellite is located above position C, as most of its view area is covering a populated landmass. In this location, it is likely that the satellite may not be satisfying all of the potential users in its view area due to reaching bandwidth limits (set by international and domestic frequency allocations), power constraints, interference effects, or other limiting factors. The dynamics of such a situation - not easily captured in a simple, closed-form analytical equation - are clearly suited to a computer simulation.

6.2 Overview of the Simulation

For the purpose of this study, a software utility has been developed to estimate the total number of billable minutes that different system architectures are able to address over a period of time in a fair and meaningful way. This goal is achieved by integrating an addressable traffic model, with the geographical coverage capability of each system's constellation and gateway architecture, and the capabilities and limitations of each satellite's payload design. Dynamics of the situation such as the motion of satellite coverage patterns on the Earth, and the variation in the market demand throughout the day, are modeled to address the differences between GEO and non-GEO systems. A fair comparison is ensured by utilizing the same addressable traffic model, and holding each system architecture to the same top level requirements listed in Chapter 3. The model can be run for different traffic distributions, and for different levels of market penetration (i.e. the addressable market can be globally reduced by a factor to simulate a fractional penetration of the MSS market).

The top level flow of the simulation is illustrated in Figure 6-2. Characteristics of the system architectures, including aspects of the constellation, antenna and payload design, and the number and location of gateway antennas, are provided in a control file (the control files used in this thesis are included in Appendix B). The simulation begins by inputting the system control files, initializing the

appropriate addressable market model, and determining both the year and duration of the simulation. At this point, the level of market penetration can also be chosen.

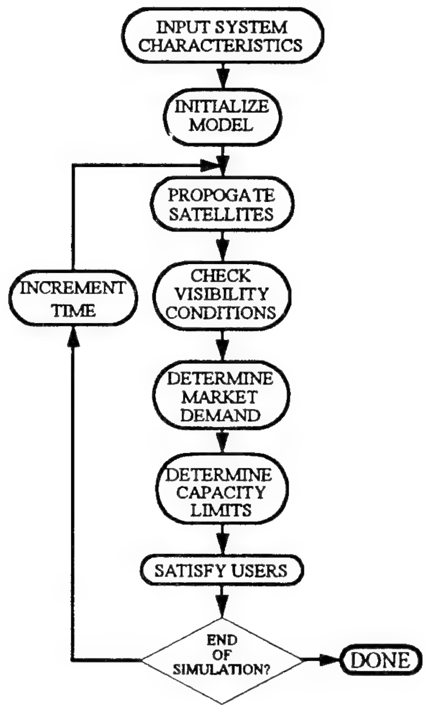

Figure 6-2 Top Level Flow of the Vircap Simulation

At each step of the simulation, the same basic procedure is followed. First the satellite positions are moved in time, and the number of addressable users are updated for the new time-of-day in each user location. Next, visibility conditions for each satellite are determined to ensure that it can connect to the PSTN through an unused gateway antenna. This check is included unless the system utilizes satellite crosslinks (communication capability between satellites within the constellation).

Provided the satellite can connect to the PSTN, the number of waiting users visible to each satellite is determined after mapping the spotbeam coverage areas on the Earth. The number of addressable users is calculated by determining the

number of traffic grids covered by each spotbeam, and estimating the number of addressable users within each grid by multiplying the percentage of the traffic grid area covered by the spotbeam by the number of waiting users. The addressable users in each beam is then reduced by the average link availability expected in that beam due to average fading conditions.

Once the addressable market for each spotbeam is determined, the next step involves satisfying as many of those users as possible, within the constraints of the system. The capacity that each satellite can address will be limited by communication constraints, in addition to the gateway and user visibility constraints. The range of other constraints that will limit satellite capacity includes available bandwidth, available power, power flux density (PFD) limits set by regulation, self-interference for CDMA systems, and the number of available gateway channels. The number of overlapping satellites at any point on the Earth can further limit capacity as they will be competing for frequency channels.

As each satellite satisfies the maximum number of users allowed within the system constraints, the available market is reduced appropriately, and the resulting estimates of addressed satellite capacity are integrated for each satellite over the length of the simulation to determine the effective system capacity for that year. These results will be coupled with the total system cost detailed in the next chapter to determine the cost per billable minute metric.

The previous description provides a brief overview of the calculation flow. The rest of the chapter will describe the details of the model, and present the capacity results for each of the modeled systems. The model description will begin with a discussion of the capacity constraints, starting with visibility and followed by the communication constraints. Once these constraints have been discussed, a more detailed discussion of the model will be presented.

6.3 System Constraints

6.3.1 Visibility Constraints

6.3.1.1 Mapping Spotbeams

In order to evaluate the potential traffic demand that falls within the coverage area of a particular spotbeam (i.e. determine mutual view between the satellite and the users), it is necessary to determine the pattern that the spotbeam makes on the Earth. A straightforward method to trace the spotbeam *footprint*, presented by Adamy [Adamy, 1974], will be reproduced here. First it is necessary to summarize some terms.

Figure 6-3 illustrates a satellite spotbeam footprint illuminating a portion of a globe. The toe of the footprint can be considered the outer point on the edge of the coverage area furthest from the subsatellite point. Conversely, the heel of a footprint corresponds to the outer edge of the footprint closest to the subsatellite point (although if the beam centroid is centered on the subsatellite point the two points will be equally distant). The heel and toe of the footprint are important in the link calculations since they represent the longest and shortest slant range distances for the footprint (unless the subsatellite point is located within the coverage area).

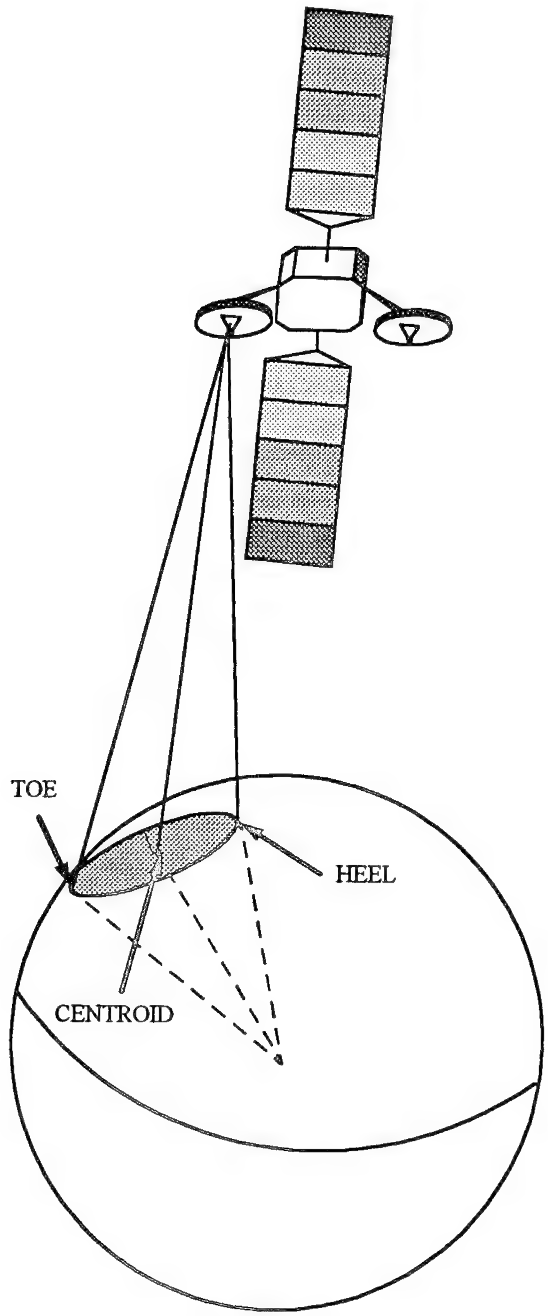

Figure 6-3 Geometry of the Spotbeam Footprint Calculation

Assuming that the spotbeam is formed in the shape of a symmetrical cone, the pattern made by the spotbeam can be drawn where it intersects with the Earth, given the latitude and longitude of the subsatellite point $(\delta_{s,} L_s)$, the nadir pointing angle of the spotbeam, η_b, and the beamwidth, $2\beta_b$. These geometrical relationships described below assume that the Earth is a sphere,

neglect propagation effects on the antenna pattern, and assume that the spotbeams have a circular cross-section.

Figure 6-3 illustrates the basic geometry of the problem as viewed from the satellite.

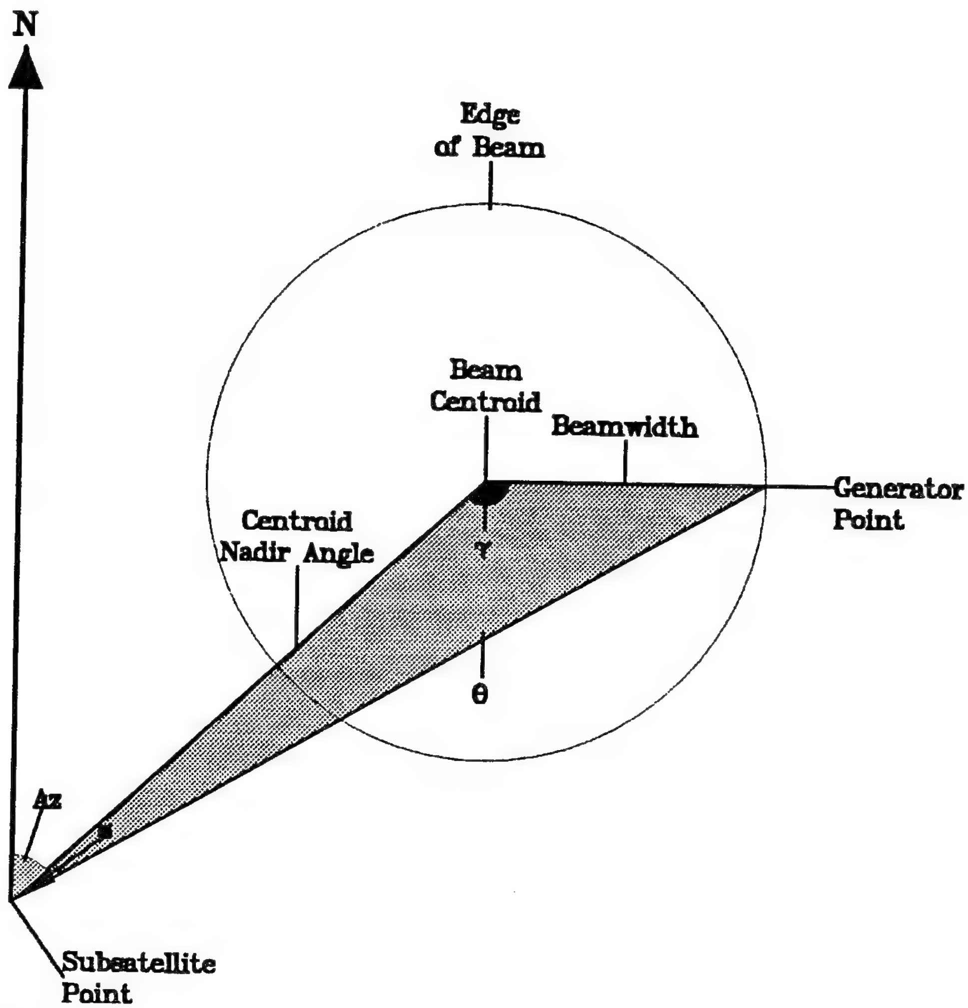

Figure 6-4 Geometry of Beam Angles from Satellite

The shaded spherical triangle represents the relationship between the subsatellite point, the beam centroid, and the edge of the spotbeam coverage area. An expression relating the generator nadir angle γ, to the angle ϕ, can be derived using basic spherical trigonometry relationships:

$$\eta_g = \cos^{-1}\left(\cos(\eta_b)\cos(\beta_b) + \sin(\eta_b)\sin(\beta_b)\cos(\gamma\ )\right)$$

(6-1)

$$\varphi = \sin^{-1}\left(\frac{\sin(\beta_b)\sin(\gamma\ )}{\sin(\eta_b)}\right)$$

(6-2)

where η_b is the nadir pointing angle to the beam centroid, η_g is the nadir pointing angle to the generator point, and β_b is half of the beamwidth.

In order to calculate the latitude and longitude of the generator point, it is necessary to convert the spotbeam pointing angle (also shown in Figure 5-2) into the equivalent angle measured from the center of the Earth, λ_g, by reworking equation (5-1).

$$\lambda_g = \sin^{-1}\left[\left(\frac{h + R_E}{R_E}\right)\sin(\eta_b)\right] - \eta_b$$

(6-3)

Finally, using equations (6-2) and (6-3), and referencing the spherical triangle illustrated in Figure 6-5,

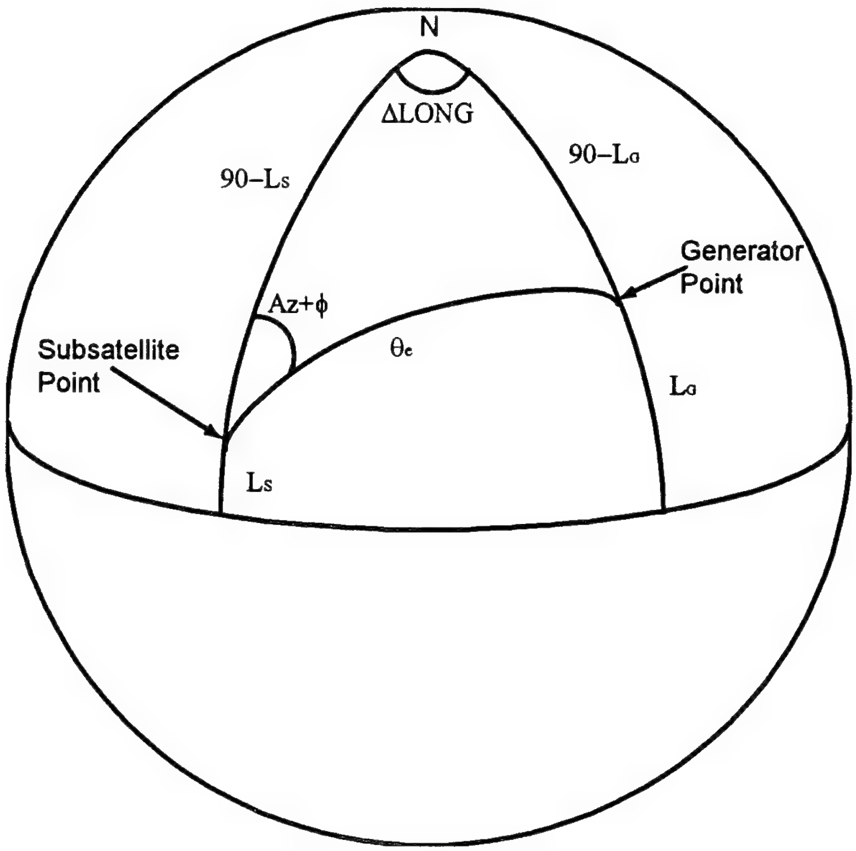

Figure 6-5 Spherical Triangle to Determine the Latitude and Longitude Position of a Generator Point.

the latitude and longitude of the generator point (δ_g, L_g) can be calculated using spherical trigonometry relationships.

$$\delta_g = \sin^{-1}\left(\sin(\delta_s)\cos(\lambda) + \cos(\delta_s)\sin(\lambda)\cos(Az + \varphi)\right) \tag{6-4}$$

$$L_g = L_s + \sin^{-1}\left(\frac{\sin(Az + \varphi)\sin(\lambda)}{\cos(\delta_g)}\right) \tag{6-5}$$

The locus, or outline, of the spotbeam footprint can then be traced by varying the generator angle γ_g between 0° and 360°, evaluating equations (6-1) through (6-5), and plotting the resulting latitude and longitude position.

Figure 6-6 illustrates an example, displaying the spotbeam pattern distribution for the modeled GEO-3 system. The smaller patterns represent spotbeams with a beamwidth of one degree, while the larger patterns represent spotbeams with a beamwidth of three degrees. The spotbeam patterns furthest from the subsatellite point appear to cover a larger area due to their projection on a linear map. The spotbeam and orbital element parameters used to create this plot are listed in Appendix B.

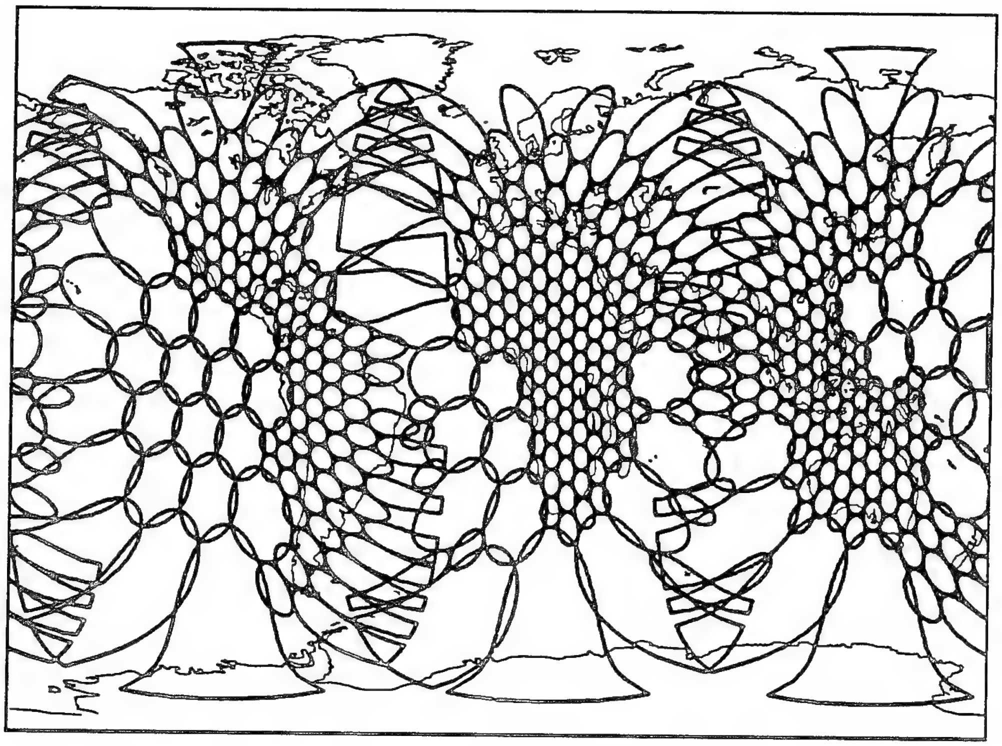

Figure 6-6 Spotbeam Distribution for the Modeled GEO-3 System.

The boundary of a satellite's viewing area above a given elevation angle can be traced in a similar manner by determining the Earth central angle λ_g subtended by the viewing area from equation (5-1), setting the nadir pointing angle, $\eta_b = 0$, and evaluating equations (6-2) through (6-5). Some other useful relationships that were utilized in the simulation can be calculated as well. The beam centroid position is determined by setting the beamwidth and the generator point equal

to zero and evaluating equations (6-1) through (6-5). The slant range distances to the heel and toe of the spotbeam footprint can be calculated by first determining the elevation angle to the satellite,

$$\varepsilon = \cos^{-1}\left(\left(\frac{R_E + h}{R_E}\right)\sin(\eta)\right) \tag{6-6}$$

and then the equivalent Earth central angle,

$$\lambda = \frac{\pi}{2} - \eta - \cos^{-1}\left(\left(\frac{R_E + h}{R_E}\right)\sin(\eta)\right) \tag{6-7}$$

where $\eta = \eta_b + \beta_b$ can represent the nadir pointing angle to the toe, or $\eta = \eta_b - \beta_b$ can represent the nadir pointing angle to the heel. The slant range distances can then be determined by substituting λ into equation **(5-2)**.

6.3.1.2 *Gateway Links*

In order to provide a worldwide voice network, gateway antennas are necessary to ensure that the voice connection from the user to the satellite can be routed through the public switched telephone network (PSTN). The first necessary step is to determine the minimum number of gateway antennas required to ensure continuous service. A small program was written to assist in this determination.

Based on standard practice in the fixed satellite services, it is assumed that each gateway antenna can operate down to a minimum elevation angle of ten degrees. Referring to **Figure 5-2**, the Law of Sines can be utilized to solve for the angular distance, θ_e (or λ), between a potential ground site and a circular orbiting satellite A that is located ten degrees above the ground station's horizon:

$$\theta_e = \sin^{-1}\left(\frac{(R_E + h)\sin\varepsilon}{R_E}\right) - \varepsilon \tag{6-8}$$

where h represents the altitude of the satellite.

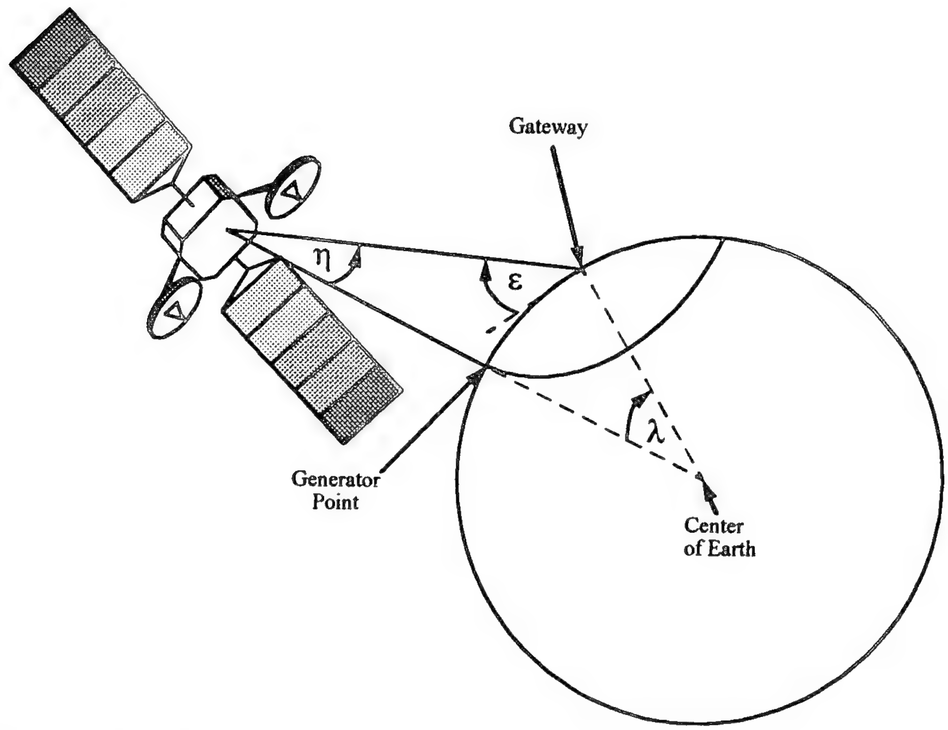

Figure 6-7 Gateway Geometry

The zone of visibility between any satellite at altitude h and the potential ground station can be drawn by calculating the locus of all the position vectors that place a satellite ten degrees above the gateway antenna's horizon. This concept is illustrated in Figure 6-7, where ε represents the 10° minimum elevation angle. The border of the gateway visibility zone can be traced in the same manner as the spotbeam footprints were previously. The nadir pointing angle can be set to zero, the angle φ can be swept from 0° to 360°, and the latitude, δ_g, and longitude, L_g, for each generator point can be calculated using equations (6-4) and (6-5).

By plotting the area serviced by each potential ground station, the program allows for the easy addition, subtraction, and movement of the gateway locations to determine the minimum number of gateway locations required for continuous service. Gateways were optimally located near population centers in order to ensure an adequate connection with the PSTN. In addition to determining gateway location, the ground selection program allows for the placement of multiple antennas at each gateway site, and line of sight statistics can be run to determine if there are any gaps in service.

The ground station software was applied to determine the minimum number of gateway sites, location, and number of antennas per site required to provide seamless coverage. The number and location of gateways (and antennas) was varied until an apparent minimum occurred. Figure 6-8 displays the resulting gateway locations for the LEO-48 system. Note that there are regions in the ocean where there are gaps in coverage. It is possible to add more gateway sites on remote islands in the ocean and erase these holes in coverage; however, it was assumed that the small traffic demand in these regions would not warrant the expense of additional gateways.

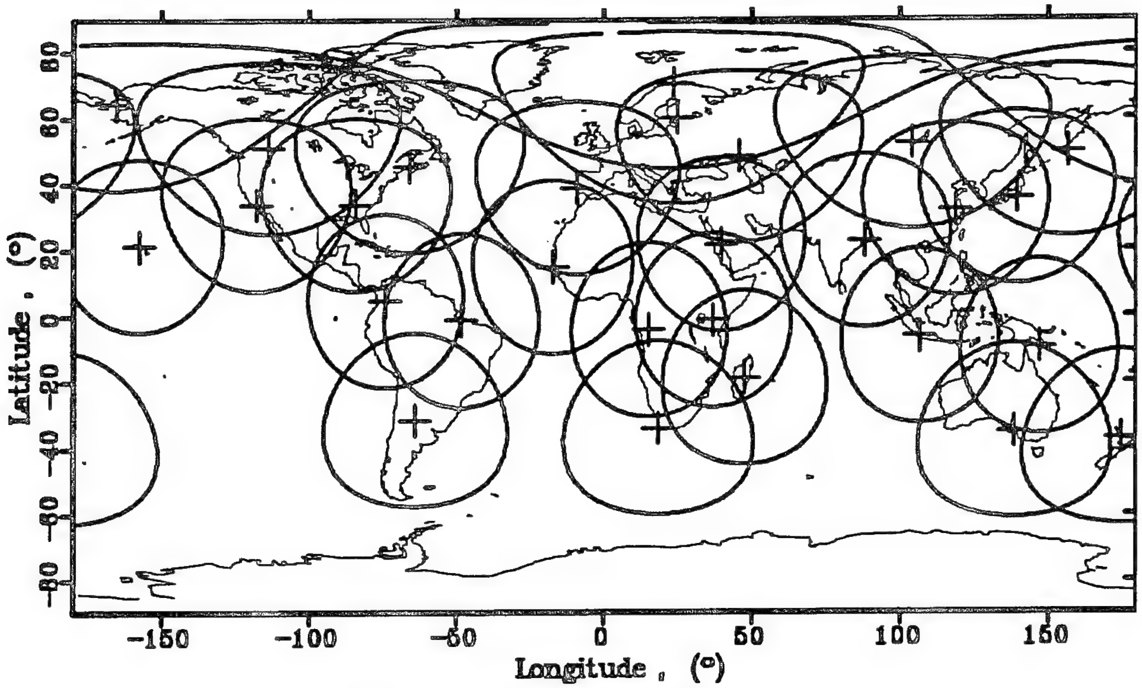

Figure 6-8 Geographic Gateway Distribution for LEO-48.

The resulting ground station sights selected for each of the modeled systems, excluding LEO-66, are listed as part of the control files in Appendix B. Ground station sights were not selected for LEO-66, modeled after Iridium, because it utilizes satellite crosslinks. Satellite crosslinks allow the system to route individual circuits from satellite to satellite (both interplane and intraplane), and do not require that each circuit be directly routed to a ground station antenna. The gateway line-of-sight checks were not included for LEO-66, and the satellite crosslinks were not modeled.

Although intersatellite links allow mobile to mobile calls, without the technical requirement to route each call directly to a gateway, calls between mobile and fixed users will still require connection to the PSTN someplace. In addition, individual countries and regional PTT's (Postal, Telegraph and Telephone authorities) will likely require that calls into their region are routed through their own gateway terminals so that they can collect a portion of the revenue. In order to ensure adequate routing through the PSTN to satisfy regional

authorities, the LEO-66 system costs included 30 gateway stations (even though the gateway and ground station links were not included in the simulation). This number of gateway stations was assumed since Iridium requires approximately 30 gateway terminals for a mature system [Babbit, 1995; Scientific-Atlanta, 1995].

6.3.2 Capacity

6.3.2.1 *Power Limits*

One of the major limits of capacity is the availability of RF power for the downlink from the satellite. Since the size and cost of a communications satellite generally scale with its power (and mass), most satellites are designed to provide just enough power to satisfy the expected market. Since the available power on a satellite is not unlimited, parts of the system will often reach the limit of available power. The RF power can be limited by the maximum power available from the batteries and solar cells, or by hardware limits set by the power amplifiers. The power amplifier limits can come in two forms: constraints on the maximum power within a single beam, or an additional limit on maximum power available to a panel, or group of beams. The latter constraint can be found on systems that share available power amongst multiple beams through a matrix of power amplifiers.

The power-limited capacity of a beam can be determined by reworking equation (5-18) to solve for the average power required per voice circuit.

$$P_t = \frac{16\pi^2 V_a \left(kT_{sys} + I_o\right) R R_{slant}^2}{G_t G_r L_c L_p L_f \lambda^2} \left(\frac{E_b}{N_o}\right) \tag{6-9}$$

The power-limited capacity in an individual beam can then be solved by dividing the available power in the beam by this average power per circuit, and multiplying by the number of TDMA frames per circuit,

$$N_{power} = \frac{P_{avail}}{P_t} N_t$$

(6-10)

where the average power per circuit is calculated using the spotbeam's average slant range.

6.3.2.2 *Power Flux Density Limits*

Power flux density (PFD) represents the power received per unit area in a bandwidth channel. Due to limits set by the ITU's International Radio Consultative Committee (CCIR), the PFD produced by a space station on the earth's surface must not exceed published levels in any 4 kHz bandwidth [CCIR, 1985]. The PFD produced on the Earth's surface can be estimated using the following equation:

$$PFD = \frac{P_t G_t L_c \lambda^2}{16\pi^2 R_{slant}^2} \left(\frac{4000Hz}{\Delta f} \right)$$

(6-11)

These maximum PFD limits, listed in the ITU Radio Regulations for each frequency band, are set in order to prevent interference with terrestrial and other satellite-based communications systems. Given the maximum PFD level allowed by the ITU, the maximum transmitted power allowed per bandwidth channel, P_{chan}, can be determined by rearranging equation (6-11).

$$P_{chan} = \frac{16\pi^2 R_{slant}^2 PFD_{max}}{P_t G_t L_c \lambda^2} \left(\frac{\Delta f}{4000Hz} \right)$$

(6-12)

Since the system should not exceed the PFD limit anywhere on the ground covered by the beam, the PFD limited power per channel for a beam should be calculated using the slant range to the heel of the spotbeam footprint. If P_{chan} represents the maximum transmitted power from the satellite allowed by

regulation, and P_{avail} represents the available satellite RF power, the maximum number of users allowed per bandwidth channel, M_{PFD}, can be calculated as follows:

$$M_{PFD} = \frac{N_t P_{avail}}{V_a P_{chan}} \tag{6-13}$$

where V_a is the voice activity factor, and N_t is the number of TDMA frames utilized per bandwidth channel (by splitting the available spectrum in time, only instantaneously transmitted signals will add to the PFD). CDMA systems operate with an N_t of one.

> *According to No. 2566 (RR28-8) of the ITU Radio Regulations, the power flux density at the earth's surface produced by emissions from a space station, for all conditions and for all methods of modulation, shall not exceed the following values:*
>
> - *-152 dB (W/m²) in any 4 kHz band for* $0° \leq \varepsilon < 5°$
> - *-152 + 0.5(δ - 5°) dB (W/m²) in any 4 kHz band for* $5° \leq \varepsilon < 25°$
> - *-142 dB (W/m²) in any 4 kHz band for* $\varepsilon \geq 25°$
>
> *where ε is the angle of any arrival in degrees above the horizontal plane [TRW, 1994].*

Unlike the S-Band, the L-Band does not have an explicit PFD limit in the Radio Regulations, since MSS has only been provided with a secondary allocation in that band. Although systems using primary, and permitted allocations have equal rights for use of the spectrum, systems operating under a secondary allocation "shall not cause harmful interference to or claim protection from stations of a primary or permitted service" [Morgan, 1989]. The only system currently planning to use the L-Band for space-to-earth links is Iridium. Although it is likely that any MSS system operating in the S-Band for space-to-

earth communications will have to operate within some practical PFD limits to avoid interfering with services operating under a primary allocation, the PFD limit check was disabled for the modeled LEO-66 system due to a lack of specific guidelines.

6.3.2.3 *Interference Limits*

As discussed in section 5.5, when receiving a signal using a CDMA system, all of the other user signals present at the receiver will appear as additive white guassian noise (AWGN). This noise is due to random correlations of the other user signals with the wanted signal. Most of the proposed CDMA systems plan to utilize direct-synchronous CDMA.

Direct synchronous CDMA (DS-CDMA) techniques combine (modulo-2 add) the spreading code (a pseudo-random binary sequence of some length) with the information sequence to implement the spreading function. This signal is then BPSK (binary phase shift keying) modulated by another pseudo-random sequence of bits characteristic of the gateway station, and transmitted. The degree of interference between two receive signals will depend primarily on the correlation between the two corresponding pseudo-random sequences [CCIR, 1985].

If the spreading codes are orthogonal, and the signals are synchronized in time, then there will be little interference between the two signals due to cross-correlation; however, if the signals are not time-synchronized, the total capacity available within a beam will be limited by interference between the received signals due to cross-correlation of the spreading codes. In order to minimize cross-correlation interference, most of the proposed systems will utilize synchronous DS-CDMA on the forward downlink since multiple signals are easily synchronized at the gateway station. However, it is much more difficult to synchronize signals from multiple, widely-dispersed mobile users in different

environments, so the DS-CDMA technique used for the return uplink will most likely be asynchronous, and the uplink capacity within a single frequency band of a beam will be interference-limited.

Viterbi and many others have derived the interference-limited capacity of an asynchronous DS-CDMA channel in the literature [Viterbi, 1995; Viterbi, 1979; Morgan, 1989]. A brief summary will be provided here.

Take the case of N_u users transmitting in the same bandwidth channel to satellite A within one spotbeam's coverage area. The power density δ_p received at the satellite from an individual handheld user transmitting at an average power, P_t, can be represented as follows:

$$\delta_p = \frac{P_t G_t G_r L_c L_p L_f M_{pc}}{\Delta f}\left(\frac{\lambda}{4\pi R_{slant}}\right)^2$$

(6-14)

where M_{pc} is the power control margin. If the system utilizes voice activity, and the power received at the satellite from each of the transmitting users is equal (within the 2 dB power control margin), the total interference noise that each received signal will experience from all of the other users can be determined by multiplying the power received per user by the number of interfering users and the voice activity, and dividing by the bandwidth of the channel. This can be represented in the following equation:

$$I_o = \frac{N_I V_a \delta_{pc}}{\Delta f}$$

(6-15)

where N_I is the number of interfering users,

$$N_I = (N_u - 1) + N_o$$

(6-16)

where N_u is the number of users transmitting within the frequency band, and N_o is the "equivalent number of users contributing interference power from other beams and frequency bands" [Wiswell, 1995]. Experience has shown that the number of interfering users can be approximated by the following equation,

$$\alpha N_u \cong (N_u - 1) + N_o$$

(6-17)

where α is approximately 1.25 [Wiswell, 1995]. By combining equations (6-15) and (6-17), the total interference power becomes,

$$I_o = V_a\left[(N_u - 1) + N_o\right]\delta_p \cong \alpha V_a N_u \delta_p$$

(6-18)

Plugging equation (6-18) into the fundamental link equation,

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r L_c L_p L_f \lambda^2 M_{pc}}{16\pi^2 \left(kT_{sys} + I_o\right) R_{data} R_{slant}^2}$$

(6-19)

results in the following equation:

$$\frac{E_b}{N_o} = \frac{P_t G_t G_r L_c L_p L_f \lambda^2 M_{pc}}{16\pi^2 \left(kT_{sys} + \alpha V_a N_u \delta_p\right) R_{data} R_{slant}^2}$$

(6-20)

which can be solved for the maximum number of users per bandwidth channel N_u, that an asynchronous DS-CDMA system can support on the return uplink due to interference.

$$N_u = \frac{\Delta f}{\alpha V_a \delta_{pc} R_{data}} \left(\frac{1}{\left(E_b / N_o\right)_{req}} - \frac{V_a k T_{sys} R_{data}}{P_t G_t G_r L_c L_p L_f} \left(\frac{\lambda}{4\pi R_{slant}} \right)^2 \right) \tag{6-21}$$

In equation (6-21) R_{slant} represents the average slant range.

6.3.2.4 *Bandwidth Limits*

As discussed in the Background chapter, the allocation and regulation of frequencies is handled at the international level by the ITU. Within the United States this task comes under the authority of the FCC. The frequencies that have been currently set aside for MSS - 16 MHz each for uplink and downlink - are quite meager. The FCC has allocated 16 MHz in both the L and S-Band to the MSS. When the FCC put forth the final rules for the licensing of MSS in the United States, they decided upon an approach to share the available spectrum amongst multiple systems. Figure 6-9 illustrates the sharing plan.

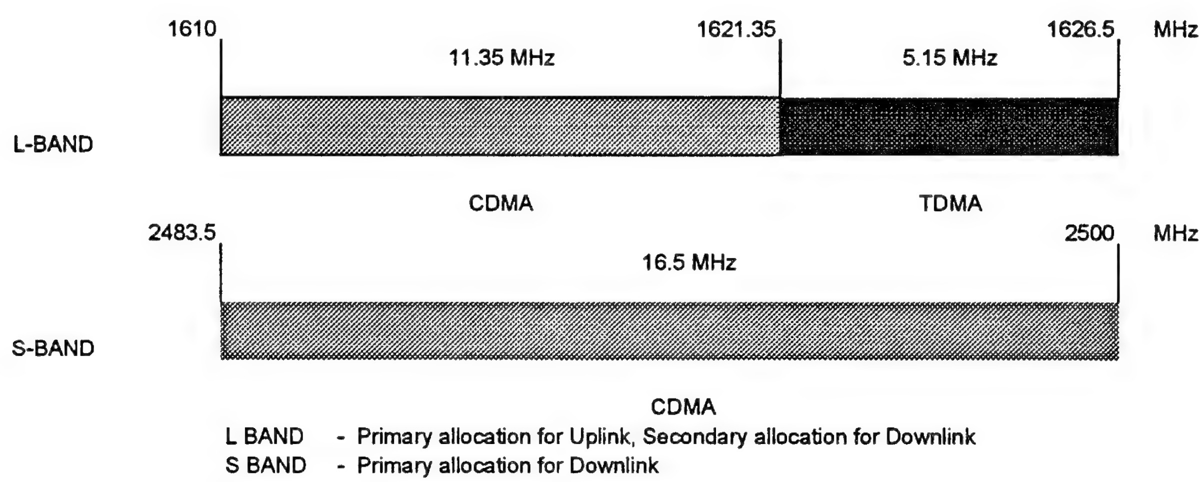

Figure 6-9 FCC Frequency Sharing Plan for MSS

Each of the proposed systems plans to segment the available bandwidth in their own way. For the purposes of this study, the channelization plan for each of the model systems was based on the plans for the proposed systems. The assumed channel plans for each of the modeled systems are listed in the following table.

Table 6-1 Channel Plans for the Modeled Systems

	UPLINK			DOWNLINK		
Modeled Systems	No. of Mobile Channels	Bandwidth per Channel (MHZ)	No. of Gateway Channels	No. of Mobile Channels	Bandwidth per Channel (MHZ)	No. of Gateway Channels
LEO-66	13	0.0315	3000	13	0.0315	3000
LEO-48	9	1.23	208	13	1.23	208
MEO-12	4	2.5	108	6	2.5	108
MITMEO-12	8	1.23	1620	13	1.23	1620
GEO-3	1	14	185	1	14	185

Unlike the mobile link, frequency allocations have not yet been assigned by the ITU (or the FCC) for MSS Feeder Links, as that is one of the major questions concerning the WARC-95 in Spain this fall. As with the mobile channels, the number of gateway channels allowed for the modeled systems were estimated based on the published feeder link plans for the mobile systems. Table 6-1 also lists the number of gateway channels assumed for each of the modeled systems. It is assumed that each of the CDMA systems will utilize dual polarization frequency reuse on the feeder links to reduce (by about half) the amount of feeder link spectrum required.

A spotbeam will not always have access to the total number of mobile-link bandwidth channels listed in Table 6-1, as a number of factors intervene. In the case of channelized TDMA systems, the same frequency band can only be reused in channels that are in spotbeams that are adequately separated spatially; otherwise interference between the channels in the beam will cause too much interference to be useful. The Iridium system plans to reuse each of the 13 frequency channels in every 12 spotbeams [Raytheon, 1995]. CDMA systems can

reuse all of the frequency channels in adjacent beams, but the addition of each additional signal on the uplink will add to the interference at the receiver for all adjacent beams and degrade both the quality of each link, and the total number of users that can be addressed within each beam.

These effects are further complicated due to the significant overlap of coverage areas from different satellites experienced for each of the nongeostationary systems. Most of the proposed systems will experience significant overlap between spotbeams on different satellites that can cause significant interference for both TDMA and CDMA systems if the overlapping spotbeams transmit signals in the same frequency band. This again will affect TDMA and CDMA systems in different ways, although the effects can be accounted for in the same way.

Channelized TDMA systems, like Iridium, cannot transmit signals in multiple spotbeams using the same bandwidth channel if the coverage area of those spotbeams overlaps on the Earth, because the lack of spatial separation between the signals will render the channels useless. In order to avoid this problem, Iridium plans to shut down spotbeams to reduce interference as the satellites approach the poles and the coverage areas begin to overlap considerably [Raytheon, 1995].

Channelized CDMA systems are affected by this overlap differently. Although overlapping spotbeams from different satellites can transmit signals in the same bandwidth channels since CDMA channels do not require spatial separation, the uplink, interference-limited capacity of that frequency band will not increase. The capacity limit will instead be shared amongst the two satellite spotbeam channels for a net gain of zero since the power transmitted by users communicating through one of the satellites will be received as noise at the other satellite's receiver.

The amount of overlap experienced by each of the systems, and hence the potential interference between overlapping beams can be considerable. Figure 6-10 illustrates how much overlap can occur by displaying 20° elevation angle contours for each satellite in the Odyssey constellation at an instant in time.

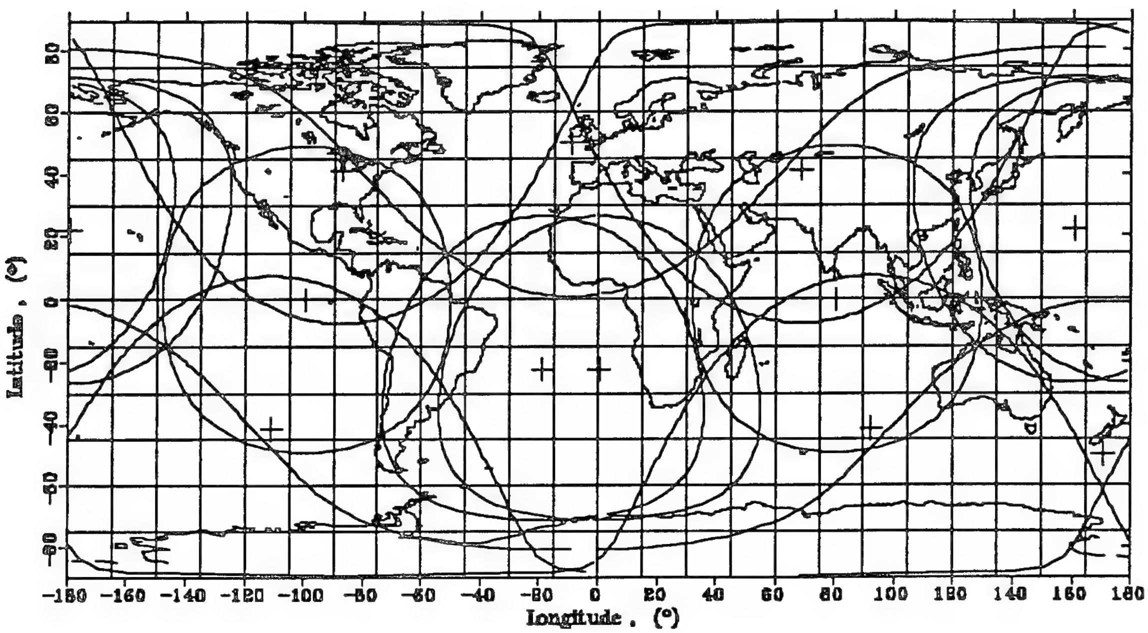

Figure 6-10 Satellite Overlap in the Odyssey Constellation

The potential interference between frequency channels in overlapping beams can be avoided by assigning different frequency channels to each overlapping beam. Because the coverage patterns created by satellites in nongeostationary constellations are in constant motion, the number and percentage of beams that overlap will be equally dynamic. Dividing the total number of available frequency channels for each spotbeam by the average number of satellites in view above each beam's centroid latitude, approximates the average number frequency channels that the system will be able to utilize, and avoids the intra-satellite, spotbeam interference issue altogether. This method is equivalent to dividing the number of frequency channels equally, on average, between the overlapping spotbeams.

The number of available channels, N_{chan}, for each spotbeam can be estimated by dividing the total number of possible channels N_{max} (listed in Table 6-1) by the instantaneous number of overlapping satellite spotbeams, $N_{overlap}$:

$$N_{chan} = \frac{N_{max}}{N_{overlap}} \tag{6-22}$$

6.4 Details of the Simulation

In Section 3.2, a simplified illustration of the *Vircap* simulation flow was provided that described the steps of the simulation at a top level. In this section, the discussion will provide more detail into the design and flow of the simulation. It will begin with a description of the orbital propagation method used, and then provide a more detailed description of the program flow.

6.4.1 Propagation of the Satellites

The satellite orbits are propagated using software based on a combination of two models used by Air Force Space Command and the NORAD. A detailed description of these models is well beyond the scope of this paper, and the reader is referred to any number of advanced astrodynamics texts [Bate, 1971; Kaplan, 1976; Battin, 1987] for a general background on perturbation theories. Darrell Herriges' Master's Thesis provides an excellent description and analysis of the NORAD perturbation models [Herriges, 1988].

Fundamentally, all orbital propagation models solve for the position vector of the satellite $\vec{r}(t)$, by integrating the two-body central-force equation,

$$m\ddot{r} = -\nabla\Phi \tag{6-23}$$

where m is the mass of the Earth, $\ddot{r}$ is the second derivative of the satellite's position vector (i.e. acceleration vector), and $\nabla\Phi$ is the gradient of the gravitational potential. The major differences between individual models involve the expression of the potential function, and the method of integration.

The gravitational field of a distributed mass, such as the Earth, is commonly represented by the following potential function:

$$\Phi = -\frac{Gm}{r}\left[1+\sum_{n=2}^{\infty} J_n \frac{P_n \cos(\Theta)}{r^n} + \sum_{n=2}^{\infty}\sum_{m=1}^{\infty} J_n^m \frac{P_n^m \cos(\Theta)}{r^n} \cos m\left(\lambda - \lambda_m^n\right)\right] \tag{6-24}$$

where r is the radius of the Earth, Θ is the co-latitude (90° - latitude), λ is the longitude, G is the universal gravitational constant, m is the mass of the Earth, P_n is the Legendre polynomial of order n, P_n^m is the associated Legendre functions of the first order n and degree m, and J_n, J_n^m and λ_n^m are constants that represent the mass distribution of interest [Pisacane, 1994].

> *This formulation conveniently partitions the gravitational potential per unit mass into three parts.*
>
> 1. *The Newtonian potential per unit mass, represented by the first or unity term in the bracket.*
>
> 2. *The zonal harmonics, represented by the second term, which depend only on the co-latitude and radius and are thus axial symmetric*
>
> 3. *The tesseral harmonics, represented by the third term, for which the terms n = m are known as the sectorial harmonics [Pisacane, 1994].*

In addition to varying representations of the Earth's gravitational potential, many models also include other third-body effects such as the Sun and the Moon in the potential function.

The two NORAD models that are used in the *Vircap* simulation are the SGP4 (Simplified General Perturbation) and the SDP4 Models. Unlike special perturbation methods which utilize direct numerical integration of equation (6-23), general perturbation methods analytically solve some aspects of the motion of a satellite subjected to perturbing forces, while using series expansions and approximations for those forces that do not yield a direct analytic solution [Boden, 1992].

The SGP4 model "includes the zonal harmonics J2, J3 and J4, coupled with certain second order secular terms" and utilizes an atmospheric model modeled with a power density function [Herriges, 1988]. SDP4 is an extension of SGP4 that also includes "doubly-averaged, first order, lunar and solar gravitational terms" and accounts for tesseral and sectoral resonances for twelve hour orbits with high eccentricities, and near circular orbits with a twenty-four hour period [Herriges, 1988]. The SGP4 routines are utilized for low altitude orbits (periods shorter than 225 minutes), while SDP4 routines are utilized for high eccentricity and high altitude orbits (periods above 225 minutes) [Cefola, 1994]. The SGP4/SDP4 software library, written in Borland Pascal 7, was obtained from Major David Vallado and Captain Daniel Fonte of Phillips Laboratory. Since this software was written to propagate a single satellite at a time, the author modified the SGP4/SDP4 library using object-oriented programming techniques to allow for the simultaneous propagation of multiple satellites.

While propagating satellites using the NORAD models, it is assumed that the relative positions between satellites in a constellation are maintained throughout the simulation. This assumption is valid as the various systems plan to maintain the constellation to preserve maximum performance. Even though the constellation is assumed to be maintained throughout the simulation, all of the perturbations available with the SGP4/SDP4 propagators were included in the run except for atmospheric drag, which was excluded to simplify the study.

6.4.2 Detailed Description of the Simulation Flow

Figure 6-11 represents a much more detailed version of the program flow. The basic flow is identical to the flow described in section 6.2. At every step of the simulation, the satellites are moved forward in time, the number of potential users in sight is determined for each beam, and the maximum number of users is satisfied within the system constraints. The remainder of this section will discuss the different elements in the simulation flow.

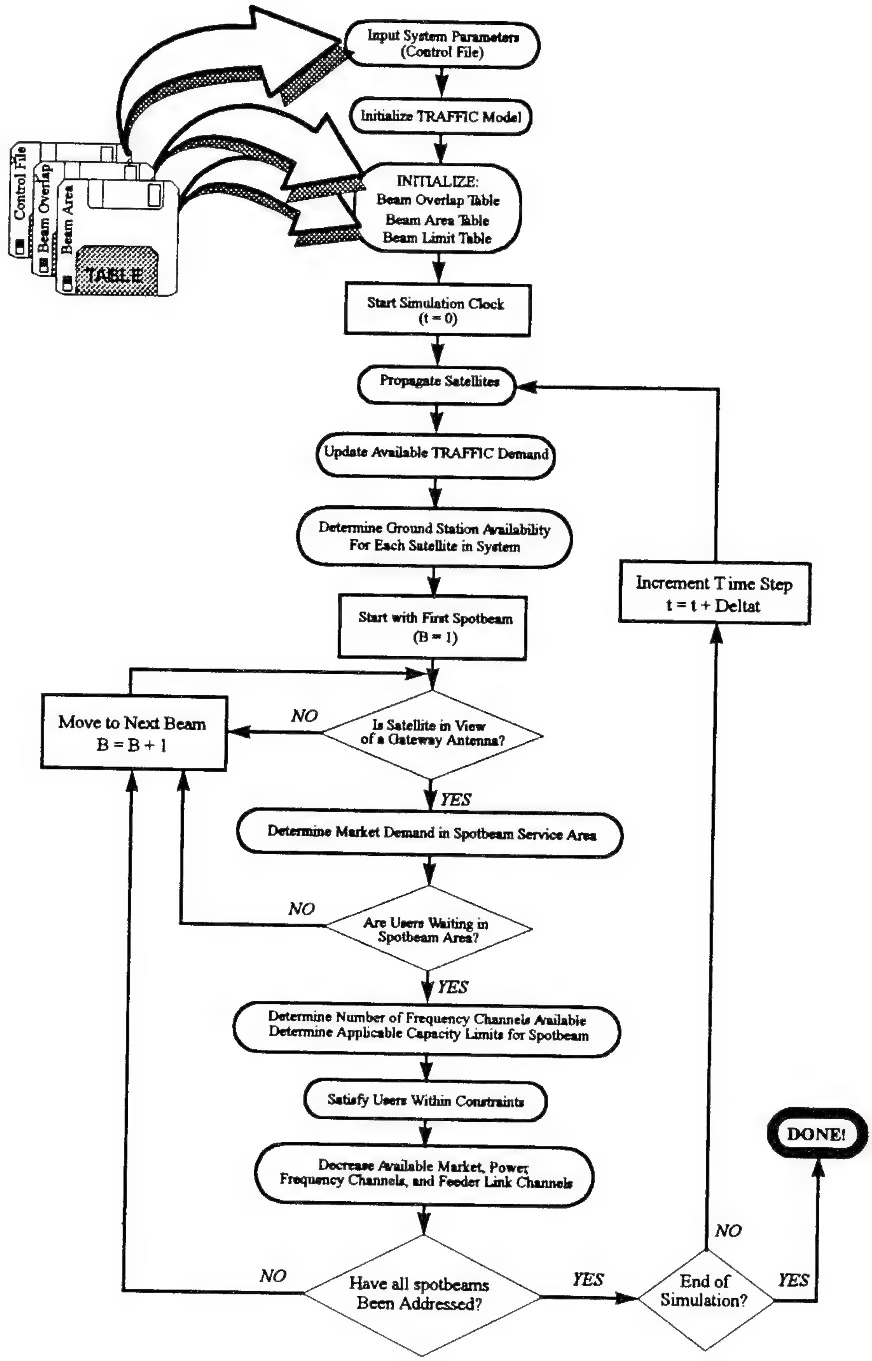

Figure 6-11 Detailed Flow of the Vircap Simulation

6.4.3 Initializing System Characteristics

Many aspects of the systems architecture must be provided in order to calculate the number of billable minutes per year. These inputs are provided to the simulation for each modeled system in the form of a control file. This file

includes details of the constellation design, the number and location of gateway antennas, and details of the communications design related to the frequency plan, modulation, multiple access scheme, forward error correction, and spotbeam coverage parameters. The control files utilized to model each of the proposed systems are located in Appendix B.

Some additional inputs required from the user that are not included in the control file include: the length of the simulation run, the size of the time step, the year of the simulation, and the maximum market penetration allowed (expressed as a percentage of the expected traffic model).

6.4.4 Initialize Traffic Model

When beginning a simulation run, the first steps in the process involve initializing the control file, choosing the simulation parameters, and initializing the traffic model. The estimated traffic model, described in Chapter 3, provides the estimated number of addressable minutes, M_{year}, of voice traffic per year in each of 288 square grids covering every 15° of longitude and 15° of latitude. The yearly traffic demand can be modified, neglecting seasonal traffic variations, to represent the expected average number of addressable minutes of traffic per day, M_{day}. This can be represented as follows:

$$M_{day_{i,j}} = \rho_{market}\left(\frac{M_{year_{i,j}}}{365}\right) \tag{6-25}$$

where ρ_{market} represents the maximum average market penetration (represented as a fraction, i.e. 50% market penetration is represented as 0.5) chosen for the simulation, and $M_{day_{i,j}}$ represents the average daily number of minutes addressable in the traffic grid located at the i^{th} longitude and j^{th} latitude index.

6.4.5 Initialize Lookup Tables

In order to simplify the calculations, and to greatly increase the speed of the model, three tables were developed that contained information that did not need recalculation at every time step. The first two tables that were developed store information on the average overlap between adjacent spotbeams (Beam Overlap Table) and the percentage of grid area covered by each spotbeam as a function of satellite position (Beam Area Table). The third table contains an array of all the capacity limits for every spotbeam on every satellite in the constellation. This table additionally contains the average power required per user, and is utilized at every time step to optimize the number of billable minutes on a system level. Because these tables are initialized at this stage of the program flow, the next sections will describe these tables in more detail before continuing with a description of the simulation flow.

1. Beam Area Table

One of the most important steps required every time the satellites are moved forward in time involves determining the number of potential users that a given spotbeam can address. Figure 6-12 displays a projection of the MITMEO-12 spotbeam pattern onto the Earth's surface, with the traffic grids displayed underneath.

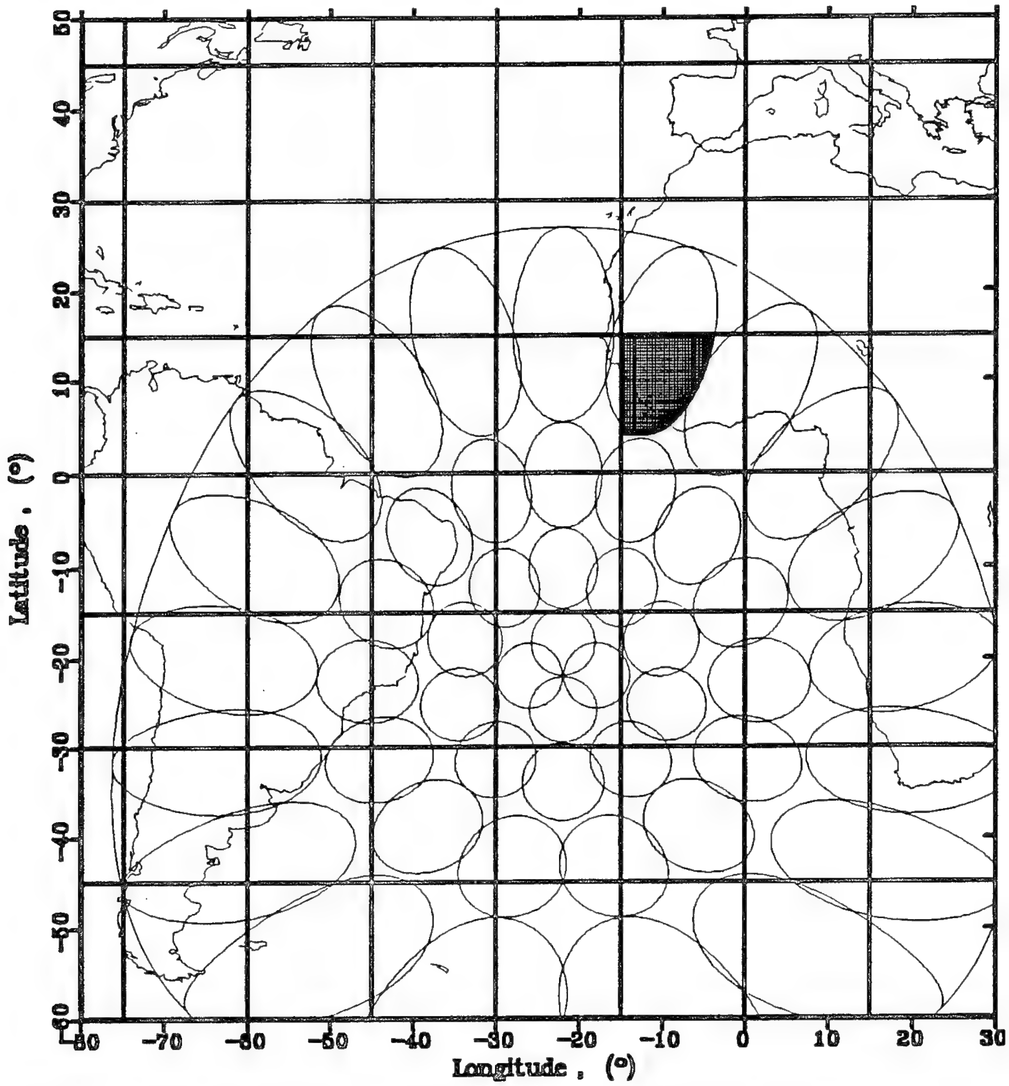

Figure 6-12 Spotbeam Coverage Areas for MITMEO-12

As is clearly illustrated, when a spotbeam is mapped onto the Earth's surface it may cover portions of many traffic grids. If only a fraction of an individual traffic grid falls within a particular spotbeam's coverage area, then only a fraction of the waiting users in that grid can be considered addressable to the spotbeam. Since it is assumed in this study that the instantaneous traffic demand is evenly distributed within each traffic grid, the number of users addressable by the spotbeam will be proportional to the fraction of the grid area falling within the beams viewing area. Determining the total number of addressable users for each spotbeam requires the determination of the

percentage of each traffic grid that falls within every spotbeam's coverage area. Although calculating areas is a simple concept, the calculations would need to be repeated for every spotbeam, on every satellite, at every time step. Because these multiple calculations would significantly slow down the computation speed of the simulation, a lookup table (Beam Area Table) was developed that contains the percentage of each traffic grid covered by each spotbeam on the satellite, for all possible subsatellite points on the Earth.

Since the spotbeam patterns assumed for each of the modeled nongeostationary satellite systems consist of symmetric rings of homogeneous (conical) spotbeams, the orientation of a satellite's position vector about its yaw axis can be ignored. If the same satellite orientation is assumed for each satellite, this simplification allows the use of a single table for all of the satellites in the constellation, provided that they are all in orbits at the same altitude.

The Beam Area Table is actually created for each satellite system, prior to the simulation, by placing the subsatellite point above each degree of latitude and longitude, projecting each spotbeam onto a linear map of the Earth on the computer screen, and computing the grid areas covered by each spotbeam by dividing the number of screen pixels that fall within both the grid and the spotbeam projection by the number of screen pixels in the traffic grid. These calculations were performed for every degree of subsatellite point latitude (-90 to 90 degrees), and were only calculated for every degree of longitude between 0 and 15 degrees East since the variation of the coverage areas repeats every time the subsatellite point crosses a longitude grid intersection.

2. Beam Overlap Table

As described previously in the section on bandwidth constraints, most of the proposed systems will experience significant overlap between the spotbeams of different satellites in the constellation. By assigning different frequency channels to each overlapping beam, the interference caused by this overlap can be avoided and the system capacity can be maximized. Determining the percent overlap between spotbeams on adjacent satellites is similar to the beam area problem, only the calculations are not as easily simplified. Constellation simulations were conducted in order to simplify the problem. It was found that over a long period of time, the average number of satellites in view varied primarily with latitude, as the symmetry of the satellite constellation averages the number of satellites in view across longitude. A Beam Overlap Table is created for each modeled system that contains the average number of satellites in view for every degree of latitude between 90° N and 90° S.

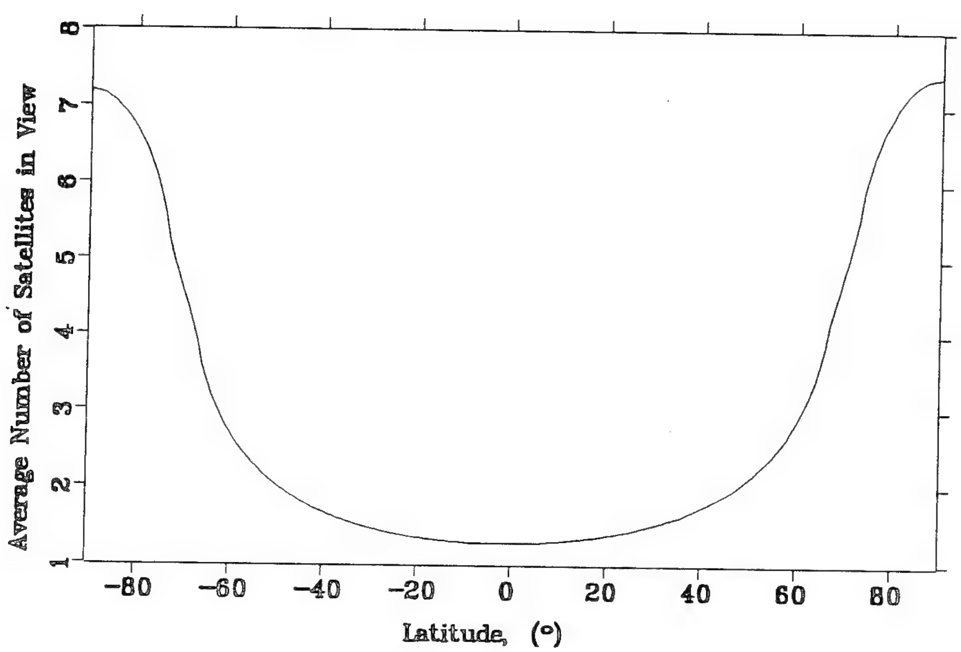

Figure 6-13 Average Number of Satellites in View for the Iridium Constellation as a Function of Latitude

Figure 6-13 displays the results of one of these simulations for the Iridium constellation. As previously described, it is clearly shown that Iridium exhibits significant overlap at high latitudes. The results of this table will be used at every step of the simulation to determine the number of available frequency channels for every spotbeam in the constellation.

3. Beam Capacity Limit Table

As with the previous lookup table calculations, an average approach was utilized in the link calculations to speed up the simulation. Many of the communications link calculations are dependent primarily on the slant range between the spotbeam and the individual user. When calculating communication link capacity constraints for each beam, the slant range to either the heel, centroid or toe of the spotbeam, is utilized, depending on which distance returns the most conservative estimate. Since each of the modeled systems utilize nearly circular orbits, the three slant range distances will remain relatively constant throughout the simulation, and many of the link calculations will only need to be evaluated a single time. The third lookup table, created to take advantage of this reduction in calculations, contains an array of the static communication link calculations for every spotbeam in the satellite system. The beam limit lookup table contains all of the capacity constraints (power, PFD, CDMA interference) for each beam in the constellation.

In addition to keeping track of individual capacity calculations, the Beam Limit Table is used to determine the order in which each spotbeam's capacity is allocated. One of the most precious resources in a satellite-based communications system is the total power available to the payload. In order to maximize the number of voice circuits satisfied by an individual satellite system, it is necessary to carefully manage that resource. Referencing the fundamental link equation for a digital system discussed earlier:

$$\left(E_b / N_o\right)_{req} = \frac{P_t G_t G_r L_s L_c L_p L_f}{k T_{sys} V_a R_{data} M_{pc}}$$

(6-26)

This equation can be rearranged to solve for the average downlink power required to satisfy each additional user within a given beam.

$$P_t = \frac{k T_{sys} V_a R_{data} M_{pc} \left(E_b / N_o\right)_{req}}{G_t G_r L_c L_s L_p L_f}$$

(6-27)

For the purposes of this study, most of the variables in this equation are held constant. The two variables actively affected by the slant range distance are the space loss, L_s, and the fading, or blockage loss, L_f. By assuming worst case space losses (i.e. using the slant range to the toe of the spotbeam) and average fading losses (using the beam's average slant range), the average downlink satellite RF power required per user can be calculated.

In order to maximize the number of addressable users, this study assumes that each satellite system will enable the spotbeams that require the least additional power per user first (likely the spotbeams closest to nadir), and working through the spotbeams towards the least power efficient links. This capacity allocation is achieved by sorting the Beam Limit Table in ascending order by the required downlink power per user before the active simulation commences.

Once the control file, the traffic model and the three tables have been initialized, the active simulation begins. The active simulation is the major loop in the simulation. At every time step the satellites are moved forward in time, and the beams satisfy as many users as possible, until the simulation has reached its end. The first step in the process is the propagation of the satellites forward in time. At this stage, the latitude and longitude position of each satellite's subsatellite

point and every spotbeam's centroid position is calculated, as well as the position vector to the sun and the corresponding sub-solar point.

6.4.6 Update Available Traffic Demand

The first step after the satellites are propagated involves determining the number of users waiting for service in each of the traffic grids. In order to estimate the instantaneous demand expected during each time step, it is necessary to assume a distribution of user activity throughout the day. It is well known that the traditional telephone circuit demand displays a significant variation with the local time, as represented in the following figure.

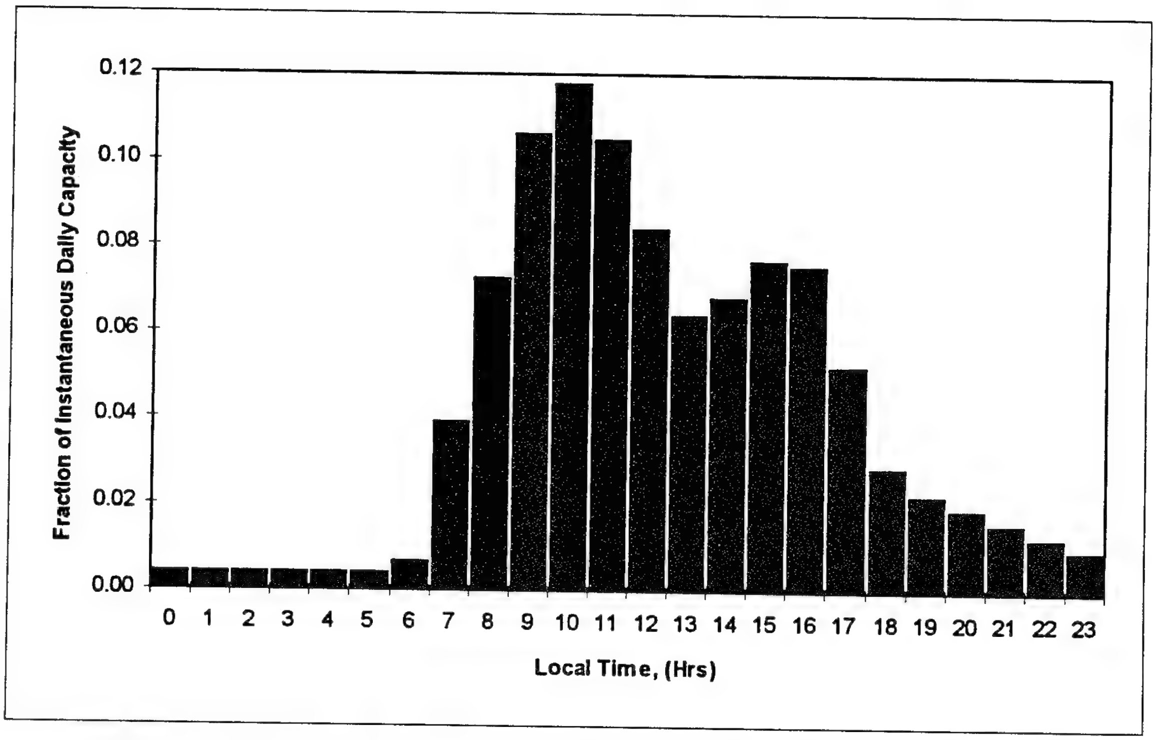

Figure 6-14 Daily Voice Traffic Distribution Measured in a Federal Building in Washington D.C. during the Summer of 1994 [Morgan, 1995].

The daily traffic distribution displayed in this figure was derived from data presented by Walter Morgan, of Communications of Clarksburg, in 1995

[Morgan, 1995]. The data comprising the distribution was collected during the summer of 1994 at a Federal office building in Washington, D.C., and closely follows time of day traffic distributions presented elsewhere [Morgan, 1989]. The two large peaks displayed between 9:00 a.m. and noon, and then again from 2:00 to 5:00 p.m., represent the worldwide busy hour. Although this data represents primarily fixed voice traffic experienced in a Federal office building, the camel distribution is considered applicable to estimate the expected daily distribution for global, fixed and mobile voice services [Morgan, 1995].

Given the location of the subsolar point, it is easy to update the local time in each of the longitude grids (the grid containing the subsolar point is considered at local noon). The maximum addressable circuits available in each traffic grid are then calculated by multiplying the average daily market available in each grid by the fraction of voice traffic expected for the traffic grid's local time of day. All of the calculations involved with determining the number of available circuits in a particular time step (including the steps performed at program initiation) are summarized in the following equation:

$$M_{Avail_i}\left[t_i\right] = \left(\frac{M_{Year_{i,J}}/360}{60}\right)\eta_{pen}\rho\left[t_i\right] \tag{6-28}$$

where η_{pen} is the market penetration factor, M_{year} is the number of traffic minutes expected during the simulation year for every i^{th} longitude and j^{th} latitude grid, $\rho\left[t_i\right]$ is the instantaneous fraction of daily traffic expected during the grid's current local time, t_i and M_{avail} is the instantaneous traffic demand expected in traffic grid {i,j} at local time t_i.

6.4.7 Gateway Line of Sight Check

The next step in the simulation involves calculating the visibility of each satellite to an unused gateway antenna. This check is determined by calculating the elevation angle from each satellite to every gateway in the system, sorting the gateways by this elevation angle in descending order, and then assigning an unused antenna at that gateway site to the satellite being checked, provided the elevation angle is above 5°. If the satellite is not in sight of a gateway, or if all of the antennas for each visible gateway are already in use, then the satellite's billable capacity for that time step is set to zero, as it will be unable to route the user signals through the PSTN. This gateway line-of-sight check is disabled for the LEO-66 system since it utilizes satellite crosslinks. Since a satellite using crosslinks can route its signals to adjacent satellites instead of directly to a gateway antenna, it is more difficult to actively model the call routing. Simulating this routing would require knowledge of the destination of each individual call - information that was not available from the traffic study. The gateway line-of-sight check was disabled to avoid this dilemma.

Once every possible satellite has been assigned to an individual gateway antenna, the Beam Limit Table is put to use. The simulation has reached the inner loop depicted in the program flow. At this stage, the simulation attempts to satisfy waiting users on a beam-by-beam basis, starting first with the spotbeam that required the least power per circuit, and moving through all the beams until reaching the beam that requires the most power per circuit. The first check in this loop is to verify that the current spotbeam's satellite can connect to a gateway antenna (except for LEO-66). If not, the simulation immediately progresses to the next beam in the table; otherwise, the simulation moves forward to determine the potential market available to the current spotbeam.

6.4.8 Determine Market Potential

Once the gateway visibility check has been accomplished, the next step involves determining the potential number of addressable users for every spotbeam in the constellation. The first step in this calculation involves determining the number of addressable users located within the spotbeam's coverage area. Since the number of users in a traffic grid is considered constant across the grid, the number of potential addressable users within the grid is a function of the percentage of the grid area covered by the spotbeam. This percentage is determined by using the Beam Area Table discussed in section 6.4.2. Figure 6-15 displays an example of how the table is utilized for the LEO-66 system, which has 48 spotbeams.

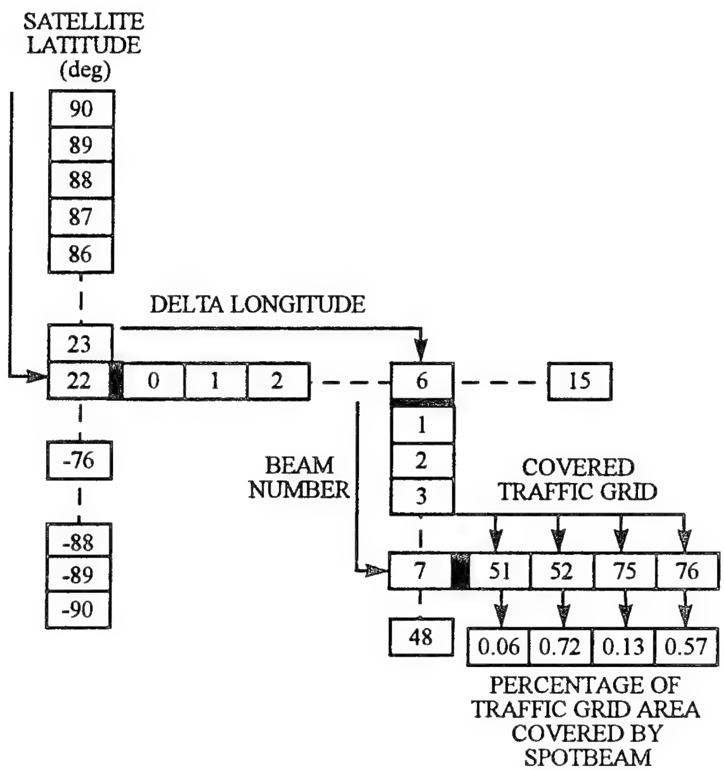

Figure 6-15 Utilizing the Beam Area Table

The first step in determining the percentage of traffic grids covered is to find the satellite's subsatellite latitude in the table (for instance 22° N in the figure). Next,

knowing the traffic grid in which the subsatellite point is located, the delta longitude position in the table is determined as the number of longitude steps to the east that the subsatellite's longitude position is displaced from the western edge of the grid (six in the figure). This position in the table contains the current grid area percentages for every spotbeam on the satellite. The grid area percentages for the seventh spotbeam can be determined by seeking down the table to the seventh beam position, and loading the coverage area percentages for all of the traffic grids in that row. In the example, the seventh spotbeam covers six percent of grid 51, 72% of grid 52, 13% of grid 75, and 57% of grid 76.

The total number of potentially addressable users in each beam can then be determined by summing the coverage area percentages for each covered grid, A, times the number of instantaneous users waiting for service in each of those grids, $M_{Avail_i}[t_i]$. This calculation can be represented in the following equation:

$$N_{adressable_b} = P_{avail} \sum_{j=1}^{N_B} M_{Avail_i}[t_i] A_j \tag{6-29}$$

where P_{avail} is the average link availability, a ratio representing the percentage of time that the communications link is usable, for the spotbeam. The link availability of the mobile satellite link will be primarily determined by the probability of fading and blockage. Spotbeams at a lower elevation angle will have a higher probability of being blocked than will higher elevation angle spotbeams, so their corresponding link availability will be lower. In addition, the availability will also be a function of the mobile user environment and the excess RF transmit power available. Since the RF transmit power and gain of the handset is limited, the link availability will be dominated by the mobile uplink. If the handheld is operating at peak power, P_t, the excess power margin that is

not needed to establish a link in LOS conditions can be determined using the fundamental link equation,

$$\frac{E_b}{N_o} = \frac{V_a P_t G_t G_r L_c L_p L_f \lambda^2}{16\pi^2 k T_{sys} RR_{slant}^2}$$

(6-30)

Since the margin in a link can be determined by the ratio between the received E_b/N_o and the required E_b/N_o,

$$M = \frac{E_b/N_o}{\left(E_b/N_o\right)_{req}}$$

(6-31)

the total margin available to combat fading and blockage, M_f, can be calculated as follows:

$$M_f = \frac{V_a P_t G_t G_r L_c L_p L_f \lambda^2}{16\pi^2 k T_{sys} RR_{slant}^2 \left(E_b/N_o\right)_{req}}$$

(6-32)

The margin is calculated using the average slant range of the beam to represent an average available margin. Given the available power margin, the availability can be solved by rearranging the simplified fading model equation described in section 5.3.3.2:

$$P_{avail} = \left(\frac{1}{a_2}\right)\left(\frac{M_f - a_1}{Ln(\pi/\varepsilon)} + a_3\right)$$

(6-33)

The availability is determined for each of the three environments, and a weighted average is computed using the expected distribution of the user environments (10% urban, 50% suburban, 40% rural).

6.4.9 Assess Capacity Limits

Now that the number of available users has been determined for the current spotbeam, the next step is to determine the maximum number of users that each beam is actually able to address. The first stage of this process is to determine the number of frequency channels available to the beam, since this will directly impact the number of satisfied users. As described in section 6.3.2.4, the number of available channels will be dependent on the average number of satellites in view. This is determined by searching the Beam Overlap Table for the average number of satellites in view at the current spotbeam's centroid latitude, $N_{overlap}$. The number of available channels, N_{chan}, is then determined as follows

$$N_{chan} = \frac{N_{\max}}{N_{overlap}} \tag{6-34}$$

where N_{max} is the maximum number of channels (from the channel plan) available to the spotbeam. Since this calculation will usually result in a non-integer value, the number of available channels is either rounded up or truncated depending on the results of a randomly generated number between zero and one. If the random number generator returns a fractional value less than the fractional portion of N_{chan}, then it is rounded up; otherwise N_{chan} is truncated. This process ensures that each spotbeam at that latitude will use the same number of channels on an average basis. This calculation is determined separately for both the mobile uplink and the mobile downlink. The number of available channels is then compared to the number of available feeder link channels. If there are fewer feeder link channels available than mobile channels,

then the available mobile channels is reduced to the number of feeder link channels available.

The next step is to determine the maximum number of users that can be satisfied within the following constraints:

1. **Available power:** First, the amount of available power is determined by comparing the maximum power limit for the beam to both the available satellite RF power and the remaining power available from the panel, and taking the smallest value. The power-limited capacity is then determined from equation (6-10), and multiplied by the number of available mobile downlink channels.

2. **Bandwidth limit:** If the system utilizes TDMA, the bandwidth-limited capacity is set at the maximum number of available channels times the number of TDMA frames utilized per channel.

3. **Power flux density limit:** If the modeled system operates under a PFD limit, the maximum PFD-limited capacity is determined by multiplying the PFD-limited capacity per channel (determined from equation (6-13)) by the number of available downlink channels.

4. **CDMA interference limit:** If the system utilizes CDMA, the maximum number of Interference-limited users is determined by multiplying the CDMA-limited capacity per channel (Equation (6-21)) by the number of available uplink channels.

The simulation then compares each of these constraints with the number of addressable users waiting within the coverage area to determine the maximum number of the addressable users that the current spotbeam is able to address.

6.4.10 Satisfy Users

Once the maximum number of users that the spotbeam can satisfy has been determined, the simulation satisfies each of the users. This step entails calculating the actual satellite power that is required to satisfy that number of

users. This can be determined by multiplying the number of users by the power-per-circuit ratio and dividing by the number of TDMA frames:

$$P_{req} = \frac{N_{users} P_{user}}{N_{frames}} \tag{6-35}$$

The amount of satellite and panel power remaining is then decreased by P_{req}.

The next step is to determine the number of uplink and downlink channels that are actually required to satisfy the users, so that the feeder link channels can be appropriately reduced. If the system operates under a PFD limit, the number of downlink channels required is determined by dividing the number of satisfied users by both the PFD-limited capacity per channel, and the number of TDMA time frames; otherwise the number of downlink channels used remains the same. If the system operates under CDMA interference limit, the number of uplink channels required is determined by dividing the number of satisfied users by the CDMA-capacity limit per channel. The number of available feeder link channels is then reduced for both the feeder uplink (subtract mobile downlink channels used) and the feeder downlink (subtract mobile uplink channels used).

Once all of the required parameters have been reduced, the number of users satisfied by the current spotbeam is integrated into the running total of billable minutes for the system. Since the simulation progresses in discrete time steps, the number of satisfied users is multiplied by the length of the time step before being integrated with the running total. The simulations run for this thesis were all conducted using a time step of three minutes.

The final step in the process involves reducing the number of waiting users in each of the traffic grids covered by the spotbeam.

6.4.11 Decrease Market Potential

The total market of addressable users at this time step is reduced for each traffic grid covered by the current spotbeam. The ratio between the number of users satisfied by the spotbeam and the number of available users waiting in the coverage area represents the fraction of users that the beam has addressed, $\delta_{addressed}$. The number of users waiting in each traffic grid covered by the spotbeam, N_{grid}, is then reduced by the following equation:

$$N_{grid} = N_{grid} - \left(A_j M_{Avail_i}[t_i]\right)\delta_{addressed} \tag{6-36}$$

Once the total potential market has been reduced, the inner loop of the simulation is repeated until all of the spotbeams in the constellation have been addressed. The same process is repeated for every time step until the time reaches the end of the simulation.

The next section will present the results of the simulation runs for each of the modeled systems.

6.4.12 Results of Simulation

The *Vircap* simulation was run for every year from 2001 to 2012 for each of the modeled systems. The actual simulations were run for a single day, at three minute steps, and the number of billable minutes obtained were multiplied by 365 to determine the number of billable minutes for the year. As discussed in the introduction, the objective of this thesis is to utilize the cost per billable minute metric to determine how well each of the model architectures can satisfy a market that is smaller than expected. In order to address that question, the simulations were run at market penetration levels of 10% and 31% of the total expected market. Most of the proposed systems are aiming for 31% to 50% of the total market, so these penetration levels model what will happen if either the

market is smaller than expected, or the individual systems are unable to capture a larger share of the market.

Figure 6-16 displays the results for the 10% market penetration case.

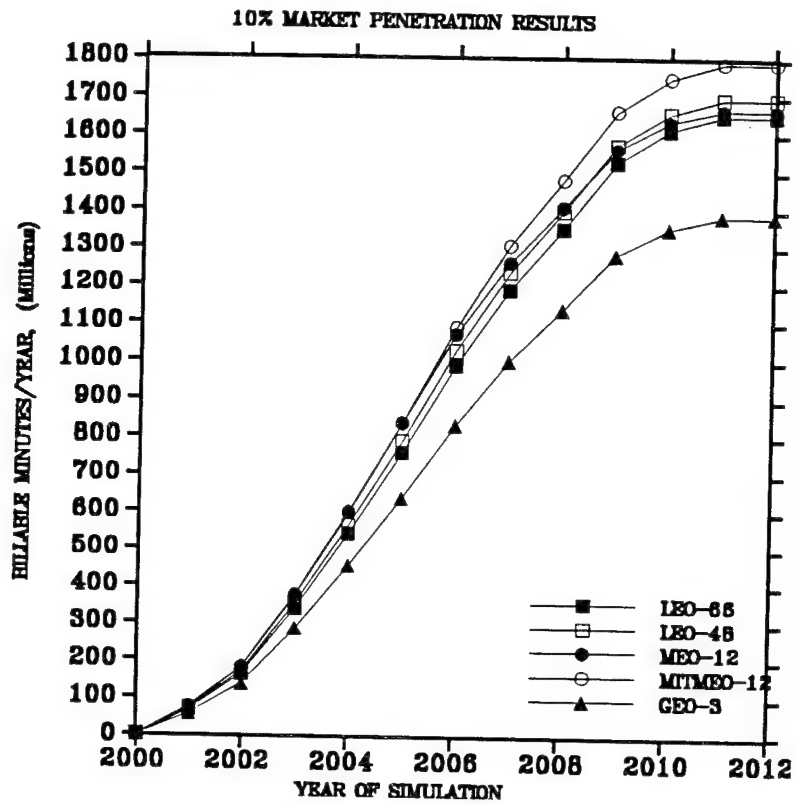

Figure 6-16 Billable Minute Results for the 10% Market Penetration Case

All of the modeled systems start at the same level in the early years, since every system is completely limited by the available market. As the market increases to a high enough level, each system can begin to reach some of the other limits before hitting the market constraint. By the late years in the simulation, the GEO-3 system has fallen the furthest behind the other systems in terms of the number of billable minutes. The system satisfying the most billable minutes is the MITMEO-12 system. All of the other systems fall in the same overall range. Of course the number of billable minutes addressed does not tell the whole story, since it only represents half of the cost per billable minute equation. Since

the purpose of a commercial system is to make money, any one of the systems could have the most competitive product if the cost to deploy the system is low enough.

The billable minute results begin to change as the market penetration is increased, as illustrated in the 31% market penetration case depicted in Figure 6-17.

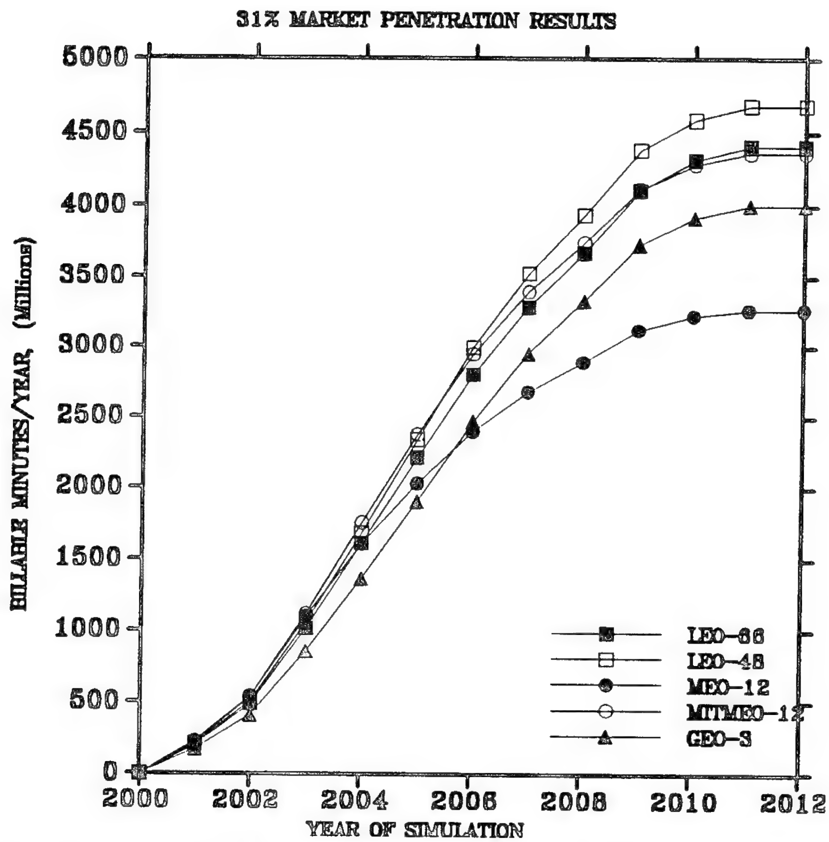

Figure 6-17 Billable Minute Results for the 31% Market Penetration Case

The most striking difference in the 31% penetration case can be seen with the MEO-12 system since it achieves the lowest billable minute capacity starting in 2007. In this case, the addressable market increased enough so that the system began reaching limits in its available power. The rest of the results appear

similar to the 10% market case with the MITMEO-12 system achieving the most billable minutes, followed by the two LEO systems and then by the GEO system.

Although total billable minutes is the important parameter to develop the cost per billable minute metric, it is useful to look at the capacity results in a different manner to gain more insight into what is happening. Figure 6-18 and Figure 6-19 display the average availabilities achieved for each system for the two market penetration cases. The average availability is determined by dividing the number of billable minutes by the total available market for a given penetration.

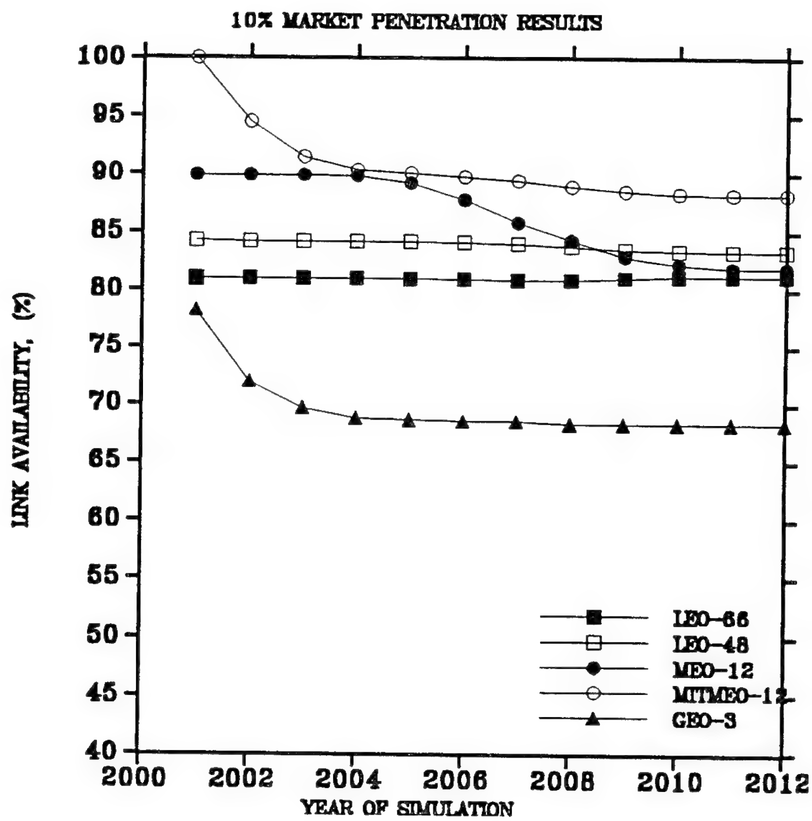

Figure 6-18 Average System Availabilities for the 10% Market Penetration Case

The average availability of a system is a function of many factors, including both visibility and capacity constraints, as well as the link availability that is primarily driven by fading and blockage of the mobile link. As expected, the

GEO-3 system attains the lowest average availability of all the systems. This is explained by the fact that the systems are primarily market limited, so that the link availability is the driving factor. Since the GEO satellites are fixed on the equator, a large portion of the spotbeams are located at high latitudes, which corresponds to much lower elevation angles. Since the probability of a signal being faded or blocked by obstructions in the signal path is primarily dependent on the elevation angle, the GEO system will experience higher fading levels, and hence a lower link availability. The average availabilities for each of the LEO systems remains fairly constant. The availabilities for the two MEO systems are the highest since their average elevation angles are higher than the other systems, although there are differences between the two systems. The MEO-12 system starts with an average availability of around 90% in the early years. As the market increases, the system begins to hit some power limits and its availability decreases. The MITMEO-12 system achieves higher availabilities, even though it uses a similar constellation design and has almost the same available RF power, primarily due to higher antenna gains.

Figure 6-19 displays the average system availability results for the 31% market penetration case.

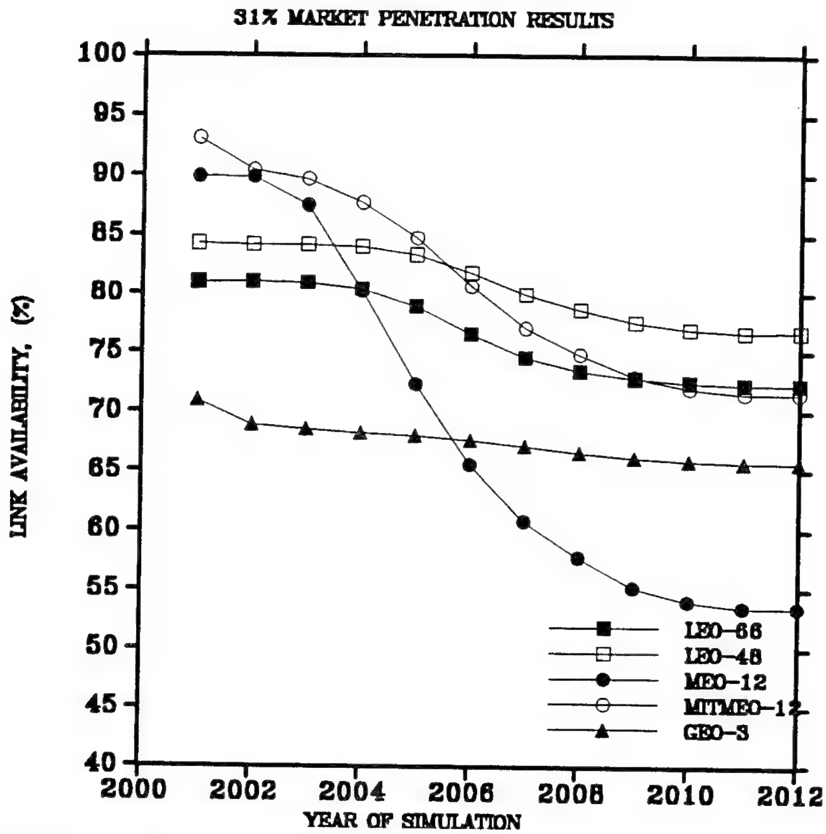

Figure 6-19 Average System Availabilities for the 31% Market Penetration Case

These results echo the capacity results as the MEO-12 system achieves the lowest availability, followed by the GEO-3 system, and the LEO-48 system achieves the best availability by the end of the twelve year system life. The interesting thing to note with these results is that it appears the two LEO systems will begin to achieve the best availabilities (and hence billable minute capacities) as the market penetration begins to grow above 30%. The MITMEO-12 system drops below LEO-48 in 2006, and then falls below LEO-66 in 2009.

Although these results must be combined with the system costs to determine how competitive each system is with the cost per billable minute, it is clear that low availabilities may turn away some potential customers, and that the systems with a higher achievable availability will have the advantage as the market begins to grow.

7. System Costs

7.1 Overview of Cost Estimating Methodology

The second half of the cost per billable minute metric consists of the Life Cycle Costs required to develop, deploy, and operate each mobile satellite system over a full twelve year system lifetime.

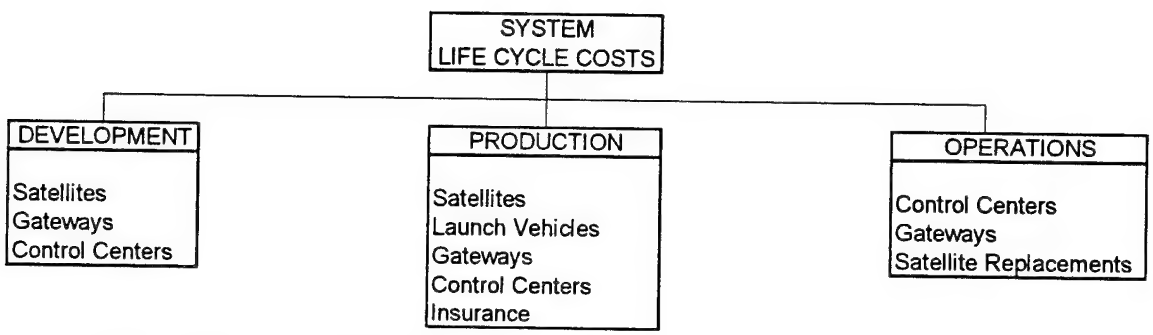

Figure 7-1 Life Cycle Cost Breakdown

The life cycle costs for each system were determined over a twelve year system lifetime, as GEO systems can easily operate for that length of time. The development, or non-recurring, phase of the system generally includes design and testing of components, prototypes and qualification units. During production, all of the satellites required to reach the Initial Operating Condition (IOC) are manufactured and launched into their defined orbits. Costs will be incurred during the operations phase by maintaining the system at the network

control center (NCC), as well as at each gateway site. LEO systems that deploy two generations will be considered to have two separate production and operation phases.

The cost function, C, associated with this approach can be summarized in the following equation:

$$C = DEV + \sum_{g=1}^{N} \left(PROD_g + OPS_g \right) \tag{7-1}$$

where DEV represents the nonrecurring costs,

$$DEV = SAT_{NR} + GATEWAY_{NR} \tag{7-2}$$

PROD represents the production, or recurring costs,

$$PROD = SAT_{REC} + GATEWAY_{REC} + LAUNCH + INSURANCE \tag{7-3}$$

OPS represents the operations, or maintenance costs,

$$OPS = GATEWAY_{OPS} + NCC_{OPS} \tag{7-4}$$

and N represents the number of generations. The costs to develop and produce the handheld units were not included in the cost function, as it was assumed that these costs would be borne by the handheld phone manufacturers. The corollary to that assumption is that revenue from the sale of handsets was also not included in the cashflow determination in the next chapter.

In order to evaluate the cost function, each of the individual cost centers (satellites, launch, gateways, operations and insurance) must be evaluated separately. The three basic methods used in cost estimating are:

1. *Engineering Buildup*

2. *Analogy*

3. *Parametrics*

each of which is discussed in a number of sources. The following overview represents a summary of information derived from Nguyen [Nguyen, 1994] and Wong [Wong, 1992].

Engineering buildup represents a "bottoms-up" estimate whereby each component is costed out separately, including estimated labor hours, and integrated into the total cost estimate. This method is generally used during the production phase when the system design is relatively fixed. This method of estimating was not considered as details of the proposed systems were often unavailable.

Cost estimating by analogy represents a comparison of the proposed system with previous programs that share similar technical characteristics. If the proposed system consists of elements that are more or less complex than the historical systems, the estimates are adjusted accordingly. This method was not used as the primary method of estimation in this study as it is more difficult to carry out a consistent estimating approach across dissimilar systems. This method was utilized in certain instances, however, to validate individual cost estimates.

Parametric, or "top-down", analysis can be the most useful cost estimating method to use prior to the production phase, as the design is in constant flux,

and many details of the technical design are unavailable. This type of analysis utilizes mathematical relationships between costs, and individual drivers (such as mass, power, weight, number of elements, etc.) that are shown statistically to have a predictable effect on the cost. These relationships are derived by applying regression analysis to available historical data, and rely on the assumption that the cost of future units will be similarly dependent on the same drivers that affected the cost of similar units in the past. These relationships are useful only when the individual drivers of the system to be studied are close to the range of the historical data. Despite these limitations, parametric analysis quickly produces consistent cost estimates that require only top-level characteristics, which makes it especially useful when conducting comparisons between different designs or approaches. Parametric analysis can consist of multiple methods ranging from "high level, one CER (cost estimating relationships) approaches, such as dollars-per-pound *rules of thumb,* to lower level multiple CER approaches" [Nguyen, 1994]. This study utilizes a range of parametric approaches as the primary method of cost estimation.

All of the cost estimates developed in this thesis are either presented in or converted to constant FY94 dollars, since the use of constant year dollars avoids confusion in the review of cost analysis results [Wong, 1992]. Cost estimates provided in other constant year dollars are converted to the FY94 base year by multiplying by an inflation factor available from the Office of the Secretary of Defense (OSD) [Wong, 1992].

Table 7-1 **Inflation Factors Based on Projections by the Office of the Secretary of Defense [Wong, 1992].**

TO	FY92	FY93	FY94
INFLATION RATE	1.040	1.037	1.034
FROM FY91	1.040	1.078	1.115
FY92	1.000	1.037	1.072
FY93	0.964	1.000	1.034
FY94	0.933	0.967	1.000
FY95	0.905	0.938	0.970

7.2 Satellite Costs

The satellite development and production costs are one of the major cost centers for each of the mobile satellite systems. Both nonrecurring and recurring costs are estimated using two versions of the United States Air Force's parametric satellite cost model, the *Unmanned Space Vehicle Cost Model, 7th Ed.* (USCM7) [Nguyen, 1994]. Satellite costs are also estimated using an alternative approach based on simple rules of thumb in order to "sanity check" the results of USCM7. The *Aerospace Small Satellite Cost Model* [Abramson & Bearden, Sept. 1993; Abramson & Bearden, Apr. 1993] was initially considered as a third estimation tool, but was not included in the study as most of the system parameters were well beyond the recommended range of the model.

7.2.1 USCM7 ESTIMATE

USCM7 provides a collection of parametric models for estimating unmanned, earth-orbiting space vehicle costs based on cost estimating relationships (CER) derived from a historical database [Nguyen et al, 1994]. The CERs included in USCM7 were derived from data collected from 19 military, 4 NASA, and 2 commercial satellite programs, with varying numbers of satellites included from each program. The models can be used to estimate recurring and nonrecurring costs for both the space vehicle (satellite bus, communications payload) and program level (program management, systems analysis, quality assurance, etc.). USCM7 describes nonrecurring costs as those costs involved with the "design, development, manufacture, and test of the qualification model," while recurring

costs include those costs associated with "fabrication, integration, assembly, and test of the space vehicle" [Nguyen et al, 1994].

USCM7 provides two comprehensive sets of CERs: the Minimum Percent Error (MPE) and the Minimum Unbiased Percent Error (MUPE). The CERs from each of these models were derived using different minimization algorithms, both of which are described in detail in the model [Nguyen, et al, 1994]. Both algorithms consist of CERs that were derived from historical data using regression processes that are "in essence weighted least squares processes".

The MPE CERs provide the smallest error of estimation, but the resulting cost estimate is biased. In other words, the sum of the residuals, R, is not zero. R can be calculated as follows:

$$R = \sum (predicted_i - actual_i)/(predicted_i) \neq 0 \tag{7-5}$$

where $predicted_i$ is the modeled estimate of the i^{th} historical cost data point, $actual_i$. The MPE model CERs are consistently biased positive (R>0), so although the error of estimation is the smallest possible using the historical data, the resulting cost estimate is always higher than the actual cost. Conversely, the MUPE CERs provide the smallest error of estimation possible while requiring that the resulting fit is unbiased, or equivalently,

$$R = \sum (predicted_i - actual_i)/(predicted_i) = 0 \tag{7-6}$$

In other words, there is an equal likelihood that the MUPE-based CERs will overestimate or underestimate the costs; however, the resulting estimate will contain more uncertainty.

Both of the USCM7 statistical methods provide a range of CER sets, allowing cost estimation from system conception, when little of the design is known, to more rigorous estimates, as detailed technical information becomes available. CERs are provided at the spacecraft, subsystem and component levels.

SPACECRAFT	SUBSYSTEM	COMPONENT
• Weight-Based	• Primary	• Primary
	• Weight-Based	• Weight-Based

Results from any of the CER sets can be combined to obtain both the recurring cost of the first production satellite, and the nonrecurring cost associated with the development of the satellite design. Each level provides two sets of CERs, one set based on primary cost drivers (i.e. the cost drivers with best fit to the historical data), and another based on weight (when more detailed information is unknown). Although it is generally more accurate to use the component level primary CERs when estimating the satellite cost, it is often necessary to utilize weight-based subsystem and spacecraft level CERs when details of the satellite system are unknown.

Nonrecurring and recurring costs for each of the mobile satellite systems have been estimated using both statistical methods. The subsystem-level, weight-based CER set was utilized when a detailed mass breakdown was available; otherwise the estimates were determined using the spacecraft-level, weight-based CER set. Although either the component-level or the primary subsystem-level CER sets would provide more accurate cost estimates, they could not be utilized due to a lack of detailed technical information regarding the proposed systems. Table 7-2 lists the mass breakdown information obtained for each of

the proposed systems, and the weight-based CER set used to estimate the satellite costs for each of the modeled systems.

Table 7-2 Mass Breakdowns for the Proposed Systems

SATELLITE WEIGHTS, (kg)	Iridium[1,2]	Globalstar[1]	Odyssey[1]	Iris[3]	Tritium[4]
Structure	Unknown	62	Unknown	138	Unknown
Thermal	Unknown	12	Unknown	60	Unknown
ADCS	Unknown	24	Unknown	20	Unknown
Electrical Power Supply (EPS)	Unknown	89	Unknown	394	Unknown
TT&C	Unknown	21	Unknown	35	Unknown
Communications	Unknown	141	Unknown	365	Unknown
AKM-Propulsion	Unknown	0	Unknown	200	Unknown
Spacecraft (Dry Mass)	607	349	1254	1212	2812
USCM7 CERs USED	S/C	Subsystem	S/C	Subsystem	S/C

[1]Information derived from FCC refilings
[2]Dry mass obtained from Kroncke, 1995
[3]MIT Mobile, 1995.
[4]Hrycenko, 1992

Although data from two commercial satellite programs are included in the model, the USCM7 CERs are still heavily weighted towards government programs (DOD and NASA). When estimating costs for a commercial satellite program, it is current practice in the industry to reduce the USCM7 cost estimates by some percentage, as government programs are perceived to be more expensive than commercial programs [Wong, 1992]. Over eight studies have been conducted in the last ten years to estimate the increased costs and inefficiencies associated with government programs. Results from these studies suggest that government programs cost anywhere from 13% to 50% more than they would if they were a commercial program [Coopers and Lybrand, 1994, Smith, Stucker, and Simmons, 1985]. A recent study conducted by Coopers and Lybrand for the Secretary of Defense, Dr. William J. Perry, has determined that due to inefficiencies caused by DOD regulations and oversight alone, product development costs for government programs average 18% higher than equivalent costs for the commercial sector. The *DOD regulatory cost premium* of 18%, averaged from data provided by ten defense contractors, can be further broken down. The average premium for firms producing electronics and

communications equipment was estimated at 25%, while aerospace equipment manufacturers averaged a 16% premium [Coopers & Lybrand, 1994]. The regulatory cost premium for developing mobile communications satellites would likely fall somewhere in this range. When coupled with other factors that tend to increase the cost of government programs even more, such as the increased uncertainty of mission requirements in military programs due to more frequent program changes [Wong, 1992], the total cost premium can be higher. In this thesis, both the nonrecurring and recurring costs derived from the USCM7 model have been reduced by 25% to correct for this bias [Plummer, 1995].

Since the USCM7 model CERs provide both the total nonrecurring cost, T_{NR}, and the recurring cost of the first production unit, T_1, in constant FY92 dollars, it is necessary to convert the estimated costs into constant year dollars for the base year of 1994. An inflation factor of 1.072 obtained from Table 7-1 was applied to the USCM7 cost estimates. Combining all of these elements, the total cost of a set of satellites, C_{sats}, could be represented by the following equation:

$$C_{sats} = \left(T_{NR} + T_1 N_{sats}\right) I_{92to94} \varepsilon_{commercial} \tag{7-7}$$

where N_{sats} is the total number of satellites, I_{92to94} is the inflation factor, and ε_{comm} is the commercial efficiency factor (or one minus the cost premium of 0.25). However, this equation would result in an overestimate of the total satellite cost due to an important effect.

The USCM7 model estimates the cost of producing a single satellite. In order to predict the production costs for a large number of satellites, it is necessary to utilize the theory of learning curves. The learning curve is a mathematical technique used to account for the observed reduction in costs as larger numbers of units are produced. These cost reductions are experienced due to

productivity improvements caused by many factors, including human learning as workers become more adept at performing repetitive tasks, economies of scale achieved by purchasing materials in bulk, and changes in design, tooling and management applied during the production phase [Stevenson 1990].

In the past, costs have been observed to go down in a somewhat predictable manner. Learning curve analysis began when T.P. Wright noticed that the "direct labor cost of producing a certain airframe decreased with experience" [Stevenson, 1990]. Since then, a large number of studies on the theory of learning curves has been conducted, and a number of models have been developed.

In general, a learning curve model describes the rate of cost reduction as a function of the number of items produced. There are two basic mathematical models currently used to estimate the rate of improvement as multiple units are produced, the unit curve and the cumulative average curve. Unit cost curves describe the "relationship between the cost of individual units," while cumulative average cost curves describe the "relationship between the average cost of different quantities of units" [Schlosser, 1975]. According to the cumulative average theory, the total cost, T, to produce N individual units can be described by the following equation:

$$T = T_1 N^{[(Ln(S)/Ln(2))+1]} \tag{7-8}$$

where T_1 is the theoretical first unit cost, and S is the cost improvement slope expressed as a fraction (i.e. S=0.95 for a 95% learning curve). Both models describe the observation that costs decrease a constant percent every time the quantity doubles.

If $B = Ln(S)/Ln(2)$, then the total cost for the first generation of satellites, C_{sats_1}, can be represented by combining equations (7-7) and (7-8).

$$C_{sats_1} = \left(T_{NR} + T_1\left(N_{sats_1}\right)^{(B+1)}\right)I_{92to94}\varepsilon_{commercial} \tag{7-9}$$

where T_{sats_1} is the number of satellites in the first generation. If a second lot of satellites is produced after the first lot, the total cost of the second generation of satellites, C_{sats_2}, can be obtained by subtracting the recurring cost of the first generation from the total cost of all the satellites.

$$C_{sats_2} = \left(T_{NR} + T_1\left(N_{sats_1} + N_{sats_2}\right)^{(B+1)} - T_1\left(N_{sats_1}\right)^{(B+1)}\right)I_{92to94}\varepsilon_{commercial} \tag{7-10}$$

Equations (7-9) and (7-10) were utilized to develop satellite cost estimates for each of the modeled systems using appropriate learning curve slopes. Robert Wong from TRW [Wong, 1992] has recommended applying a 95% curve when under 10 satellites will be produced, a 90% curve when 10 to 50 satellites will be produced, and an 85% curve when 50 to 100 satellites will be produced. These learning curve slopes have been applied to the cost estimates presented in this thesis. Table 7-3 lists the resulting satellite cost estimates using both statistical methods.

Table 7-3 USCM7 Satellite Cost Estimates

MODELED SYSTEMS	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
FIRST GENERATION					
Operational Satellites	66	48	12	12	3
Spare Satellites	14	8	2	2	1
SECOND GENERATION					
Operational Satellites	66	48	0	0	0
Spare Satellites	14	8	0	0	0
Learning Curve Slope (%)	85	85	90	90	95
MINIMUM PERCENT ERROR ESTIMATE					
FIRST GENERATION COSTS ($M)	$2,113.34	$932.32	$1,686.58	$1,118.49	$1,963.73
SECOND GENERATION COSTS ($M)	$1,340.35	$578.02	$0.00	$0.00	$0.00
MINIMUM UNBIASED PERCENT ERROR ESTIMATE					
FIRST GENERATION COSTS ($M)	$1,876.85	$770.01	$1,496.28	$931.33	$1,741.82
SECOND GENERATION COSTS ($M)	$1,192.14	$480.82	$0.00	$0.00	$0.00

7.2.2 Rules-of-Thumb Approach

Since the satellite segment of each mobile satellite system can represent a significant fraction of the total system cost, an alternative estimating approach using an industry *rule-of-thumb* relationship was utilized to cross-check the USCM7 results. This *rule-of-thumb* represents a relationship between the dry mass of a satellite, and its first unit cost. Industry experience has shown a trend of $77,000 (FY $94) per kilogram of dry mass for current mobile satellite systems.

Satellite nonrecurring costs generally range from three to seven times the recurring cost of the first satellite off the production line, depending on the complexity of the satellite design [Lovell, 1995]. Although Wong has suggested applying a nonrecurring factor of two to three times the first unit cost to determine the nonrecurring cost for a standard satellite design [Wong, 1992], the proposed mobile satellite systems do not represent standard designs. Industry cost analysts generally assume a nonrecurring factor of two for a new design based on current practices, a factor of three for a state of the art design, and a factor ranging from four to five when pushing the state of the art [Plummer, 1995]. If a significant amount of design heritage is present in the system design, such as using a standard bus, it may be necessary to reduce these factors.

Since the nonrecurring costs can have a large effect on the resulting cost of the satellite system, it was necessary to survey the nonrecurring to recurring cost ratios experienced by previous communication satellite programs. The communication satellite programs included in the USCM7 model include the DSCS-IIIA, FLTSAT-1, GPS Block 1, GPS Block II/IIA, Intelsat-IV, Marisat, NATO-3, TACSAT, and TDRSS programs. An average of the nonrecurring to recurring cost ratios for all of these programs, excluding follow-on production blocks, resulted in an average nonrecurring factor of 3.44 [Burgess, 1995]. Since some of the proposed mobile satellite systems are pushing the state-of-the-art, it is likely that some of them may exceed this average.

Providing worldwide, handheld phone service to mobile users from moving satellites certainly creates a design challenge. With moving satellites and moving users, individual phone calls will need to be actively transferred between adjacent spotbeams and satellites, while the transmitted power will need to be closely controlled both to reduce interference and to conserve satellite power. Although all of the proposed systems will need to push the state-of-the-art in order to deploy and operate a complex communications network, each will do so in unique areas.

Many industry analysts consider the LEO designs the most complex and challenging of all the systems due to both the large number of satellites and the call handoffs required at their low altitudes. A nonrecurring factor of five was assumed for the LEO-48 system to represent these design challenges. The Globalstar system plans a satellite production rate of 56 satellites in a few years, which exceeds any satellite production rate ever achieved in the commercial satellite world [Gaffney, 1994]. These production rates will require mass production techniques that correspond to a higher initial investment.

The LEO-66 system was modeled with a higher nonrecurring factor of seven, representing its more complex design. The Iridium system plans to achieve satellite production rates surpassing Globalstar. The Iridium partners have developed a 12,000 square-foot factory capable of handling five satellites simultaneously [Scott, 1995]. When the factory is up and running, Motorola claims that a satellite will be completely built in less than 21 days, and will finish a satellite every five days [Scott, 1995]. In addition to the high up-front costs required to develop such a capable mass production facility, the Iridium payload design is also considerably more complex than Globalstar. The Globalstar satellites have been designed to operate as simple bent-pipe repeaters, while the Iridium satellites will utilize onboard digital signal processing techniques and active call switching, routing each signal through multiple satellite crosslinks, requiring precise synchronization in time. All of these factors contribute to the higher nonrecurring factor assumed for the LEO-66 architecture.

A lower nonrecurring factor of three was assumed for both MEO systems and the GEO system. Although each of these systems will be pushing the state-of-the-art in a number of areas, including the potentially large antennas that may be required for the GEO system and the exposure of the MEO systems to the radiation belts, the proposed systems will utilize designs based on a standard bus, and their production schedules, although agressive, are within the bounds of current practice in the industry.

Once the nonrecurring and theoretical first unit costs have been estimated, calculation of the total satellite production costs for the first generation proceeds as before with the total first generation cost determined with equation (7-11),

$$C_{sats_1} = \left(T_{NR} + T_1 \left(N_{sats_1} \right)^{(B+1)} \right) \tag{7-11}$$

and the second generation costs by equation (7-12),

$$C_{sats_2} = \left(T_{NR} + T_1\left(N_{sats_1} + N_{sats_2}\right)^{(B+1)} - T_1\left(N_{sats_1}\right)^{(B+1)}\right.$$

(7-12)

The only difference between these equations and the previous ones, other than the estimated T_1 costs, is that the costs do not need to be adjusted since the \$77 K/kg *rule of thumb* relationship was derived from commercial satellite programs, and provides costs in constant FY94 dollars. The resulting cost estimates determined from the \$77 K/kg *rule-of-thumb* for the modeled systems are listed in the following table.

Table 7-4 Rule-of-Thumb Satellite Cost Estimates for the Modeled Systems

MODELED SYSTEMS	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
First Generation Satellites	80	56	14	14	4
Second Generation Satellites	80	56	0	0	0
Dry Mass, (kg)	607	349	1254	1212	2812
Learning Curve Slope (%)	85	85	90	90	95
FIRST GENERATION COSTS ($M)	$1,666.27	$719.98	$1,194.52	$1,154.77	$1,351.23
SECOND GENERATION COSTS ($M)	$937.26	$409.93	$0.00	$0.00	$0.00

7.2.3 Comparison of Satellite Cost Model Results

Figure 7-2 illustrates a comparison between the claimed first generation satellite costs of the proposed systems with the estimated first generation costs obtained from the USCM7 model and the *rule-of-thumb* model. The claimed costs for the Iridium, Globalstar and Odyssey systems were compiled from their recent refilings with the FCC in November 1994 [Motorola, 1994; Loral/Qualcomm, 1994; TRW, 1994], while the claimed costs for Tritium were derived from a paper presented by personnel from Hughes Aircraft Company at the Pacific Telecommunications Conference in 1992 and converted to constant FY94 dollars [Hrycenko, 1992]. The claimed costs represent both the nonrecurring and recurring costs associated with deploying their first generation of satellites.

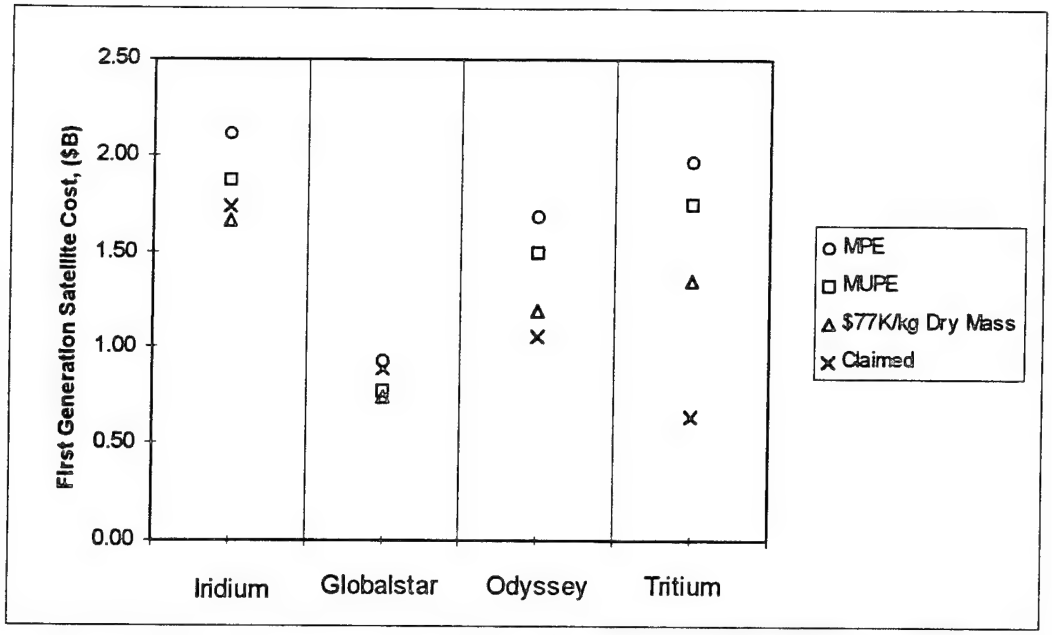

Figure 7-2 Comparison of First Generation Satellite Estimates with Claimed Costs for the Proposed Systems.

Overall, the cost comparisons with Iridium, Globalstar, and Odyssey's claimed costs look quite reasonable. Although the comparisons with Tritium appear off the mark, the differences can be easily explained. The Iridium, Globalstar and Odyssey systems have all been licensed by the FCC, and their refilings with the FCC provided relatively detailed technical and cost data that had been refined from their first filings years earlier. On the other hand, Tritium's claimed costs were based on a couple of presentations in late 1991 and early 1992 that were not meant to provide rigorous cost estimates. Indeed, the costs were quoted at $150 M (FY92) per satellite, which appears to be a bit low since the cost of the MSAT satellite, launched in early 1994, has been quoted at $250 M (FY94) [Shapiro, 1995] and that satellite is less capable than the satellites proposed for the Tritium system (although it is not clear what is contained in the $250 M number). Another caution regarding the Tritium estimates is that the dry mass of the Tritium satellite is more than 82% above the recommended range of the USCM7 model, and should not be used.

The $77 K/kg *rule-of-thumb* method was chosen to estimate the first and second generation satellite costs since it could be consistently applied for all of the systems, while the USCM7 model could not be used for Tritium. The $77 K/kg estimates also appeared to most closely predict the proposed systems' claimed costs as well. Although the USCM7 models could indicate that the proposed costs for the Iridium and Odyssey satellites should be higher, they probably overestimate the expected costs since their estimates were obtained using the spacecraft dry mass CERs instead of the subsystem-level CERs. The USCM7 cost estimates for the Globalstar system, obtained using the subsystem CERs since a detailed mass breakdown was available, more closely predicts the claimed costs.

7.3 Launch Costs

Launch costs often make up half of the total cost required to develop and deploy a communications satellite today [Saunders, 1994]. Indeed, one of the main arguments put forth by industry skeptics against LEO-based mobile satellite systems has to do with the high cost required to launch a large number of satellites into orbit. Although the proposed systems will want to utilize inexpensive and reliable launch systems to reduce these costs, published launch strategies also indicate a desire to purchase launch services from foreign providers in the former Soviet Union and China to assist penetration into the huge potential market in those areas of the world. Although a detailed analysis of the proposed MSS launch plans is beyond the scope of this thesis, it is clearly necessary to carefully evaluate the total launch costs for each of the model systems.

The estimated launch costs were closely modeled after the published launch plans of the proposed systems when information was available. Table 7-5 lists the satellite capacity of a range of launchers for each of the proposed systems.

Table 7-5 **Number of Satellites per Launcher for the Proposed Systems.**

NUMBER OF SATELLITES PER LAUNCHER					
Launcher	Iridium	Globalstar	Odyssey	Iris	Tritium
Delta 2	5	4	N/A	1	N/A
Atlas II	N/A	N/A	2	N/A	N/A
Ariane 4	N/A	N/A	N/A	2	N/A
Ariane 5	N/A	N/A	N/A	N/A	1
Zenit	N/A	12	N/A	N/A	N/A
Proton	7	N/A	N/A	N/A	N/A
Long March	2	N/A	N/A	N/A	N/A

The most detailed launch information available in the literature concerned the Iridium system. Iridium has currently signed contracts with Krunichev Enterprise of Moscow to purchase three Proton launches of seven satellites each from the Baikonur Cosmodrome in Kazakhstan [Marcus, 1993]. The first two Iridium satellites will be launched by China Great Wall Industries in July 1996 on the Long March 2C [Furniss, 1994]. The launch contract also calls for five additional launches of two satellites each [Defense Daily, 1994]. The 40 remaining Iridium satellites will be launched on eight Delta II vehicles from Vandenburg AFB, CA starting in 1996 [Ayer, 1995].

Globalstar Telecommunications, Ltd. has signed contracts with both McDonnell Douglas Corporation and the Ukrainian firm NPO Yuzhnoye to launch the first 56 Globalstar satellites. The McDonnell Douglas contract includes the launch of the first four Globalstar satellites onboard a two-stage Delta II rocket from Cape Canaveral, FL in 1997, and includes options for an additional five launches of four satellites each [Globalstar, 1995]. The contract with NPO Yuzhnoye calls for 36 satellites to be launched twelve at a time onboard three Zenit-2 rockets in 1998 [Space News, 1995].

None of the remaining systems have signed contracts with launch service providers to date. TRW has stated that they have requests for proposals out "to all the major launch providers around the world," although they do not plan to announce anything for a while [Mobile Satellite News, 6 April 1995]. They expect to launch the satellites two at a time on an Atlas IIA or IIAS and/or an

Ariane 42L [Hulkower, March 1995]. "The payload weight and size is such that an Ariane 5 launch vehicle is required" to loft a Tritium satellite into GTO [Hrycenko, 1992]. The MIT class design, Iris, has published a requirement for six launches of one satellite each onboard a Delta 2 rocket, and an additional launch of eight satellites, two at a time, on board an Ariane 4 rocket [MITMobile, 1995].

This compiled launch strategy data was combined to determine the total number of launches required to deploy and maintain each system throughout a twelve year system lifetime. The modeled number of launches required per satellite generation is listed in Table 7-6. Each system was required to launch all on-orbit and ground spares as well as the operational satellites in order to model the additional launch costs required to maintain the constellations. Since the satellite design for each of the LEO generations is assumed to be identical, the number of second generation LEO launches were also assumed to be identical.

Table 7-6 Number of Launches per Launcher for the Model Architectures.

Number of Satellites	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
Operational Satellites	66	48	12	12	3
On-Orbit Spares	14	8	0	0	1
Ground Spares	0	0	2	2	0
Launcher	NUMBER OF LAUNCHES PER GENERATION				
Delta 2	9	5	N/A	6	N/A
Atlas II	N/A	N/A	7	N/A	N/A
Ariane 4	N/A	N/A	N/A	4	N/A
Ariane 5	N/A	N/A	N/A	N/A	4
Zenit	N/A	3	N/A	N/A	N/A
Proton	3	N/A	N/A	N/A	N/A
Long March	7	N/A	N/A	N/A	N/A

Now that the launch providers and the number of launches have been determined, it is necessary to estimate the total launch costs. Table 7-7 lists a range of launch costs for each of the launchers that represent the variations in launch costs observed in the last few years [Hovden, 1995]. The modeled values

were selected from this range based on a best estimate, or on published contract price information when it was available.

Table 7-7 Current Range of Launcher Costs and Modeled Estimates.

Launcher	RANGE FY94, $M	MODELED FY94, $M
Delta 2	45 - 60	50[1]
Atlas II	60 - 80	65
Ariane 4	90 - 120	100
Ariane 5	105 - 125	110
Zenit-2	35 - 65	40[2]
Proton	35 - 75	40[3]
Long March	20 - 55	45[4]

[1] Satellite News, 1994.
[2] Space Business News, 17 May 1994.
[3] Mobile Satellite Reports, 15 March 1993.
[4] Furniss, 1994.

The resulting final launch costs (excluding insurance) for each of the model systems is listed in Table 7-8.

Table 7-8 Estimated First and Second Generation Launch Costs for the Model Architectures.

LAUNCH COSTS FOR THE MODELED SYSTEMS ($M FY94)					
MODELED SYSTEMS	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
First Generation Launch Costs	885	370	455	700	440
Second Generation Launch Costs	885	370	0	0	0

As expected, the two LEO systems require the largest investment cost to launch both generations into orbit, followed by the GEO system, and then the MEO-12 system. The high cost of the MITMEO-12 system stands out due to its reliance on the high cost of four Ariane 4 launches. If those satellites could instead be launched on lower cost launchers, like the newly proposed Delta 3, the costs would decrease significantly.

7.4 Insurance

Three general types of insurance coverage that might apply to a mobile satellite system include: Pre-Launch Insurance, Launch Insurance, and In-Orbit Insurance. Details regarding each type of launch insurance can be found in a number of sources [Kuskuvelis, 1993; Stockwell, 1983; Hill, 1983]. Pre-launch insurance covers the development of the launch vehicle and the satellite, testing and transport to the launch site up until either their integration on the launch pad, or until launch vehicle ignition. Launch insurance extends coverage for satellite loss or damage during launching, transfer orbit operations and through the on-orbit checkout phase. Coverage expires when the satellite is pronounced operational in its nominal orbit. In-orbit insurance generally covers the operator during the satellite mission against potential loss of operational capability after the satellite is deployed and operational [Kuskuvelis, 1993].

The major risk period for any satellite system occurs during the launch period, "during the first few minutes when the vehicle leaves the pad" [Kurland, 1993]. Indeed, the "majority of satellite losses, 76%, occur during the launch phase, 15% occur during early orbit and 9% when the satellite is in orbit" [Shapiro, 1995]. For the purposes of this study, it is assumed that each of the systems will purchase launch insurance to cover this period of greatest risk. Damages and failures to satellites in orbit will be covered through the use of in-orbit spares.

Although launch insurance rates have been seen as high as the 30% rate paid recently for the MSAT launch, current launch insurance rates generally range from 15% to 22% of the insured value [Shapiro, 1995], which is considered as the combined value of the launch vehicle and the satellites inside [Lovell, 1995]. The launch insurance rates depend on the "size, value, and complexity" [Shapiro, 1995] of the satellite and the reliability of the launch vehicle. Related insurance concerns can also extend to the use of some foreign launchers. Indeed, it has been noted that one "problem that the Russians face is that any company or

organization wanting to use Proton probably would pay 5% of launch cost for political instability insurance" [*Mobile Satellite Reports*, 2 Aug. 1993]. For the purposes of this study, a launch insurance rate of 20% has been assumed for each of the systems and all of the launchers. The total launch insurance cost, T_{ins}, for each of the systems can be estimated by multiplying the sum of the total satellite costs, T_{sats}, and the total launch costs, T_{launch}, by the insurance rate:

$$T_{ins} = 0.2\left(T_{sats} + T_{launches}\right) \tag{7-13}$$

The launch insurance results are listed in Table 7-9.

Table 7-9 Estimated Launch Insurance Costs for Each of the Modeled Systems.

MODELED SYSTEMS	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
FIRST GENERATION					
Average Satellite Recurring Cost ($M)	$16.7	$10.5	$64.6	$62.5	$175.4
Total Launch Insurance ($M)	$444.8	$191.1	$272.0	$315.0	$228.3
SECOND GENERATION					
Average Satellite Recurring Cost ($M)	$11.7	$7.3	$0.0	$0.0	$0.0
Total Launch Insurance ($M)	$364.5	$156.0	$0.0	$0.0	$0.0

7.5 Gateways

The number of gateways required for the proposed systems to provide global coverage was generally not available in either the FCC filings or the open literature. As previously detailed in the system capacity chapter, the minimum number of gateways and antennas necessary to ensure that each satellite has continuous contact with a gateway was estimated by modeling the dynamic satellite-to-ground link. The Iridium system alone was not modeled since it plans to utilize intersatellite links to reduce the number of gateways required. The LEO-66 system was assigned 30 gateway sites each, since the Iridium system plans to utilize approximately 30 sites in order to provide global coverage [Scott, 1995; Curley, 1995].

A Ka band tracking ground station is estimated to have a recurring cost per antenna of about $1.5 M for LEO systems, $2.5 M for MEO systems, and $5 M for GEO systems [Lovell, 1995]. These costs vary depending on the slew rate and noise figure requirements and the amount of redundancy required, and include all of the hardware necessary to convert the signal down to baseband. The connection of the baseband signal to the PSTN is costed separately. Each gateway is expected to require multiple antennas to ensure continuous global coverage, and will require one backup antenna per site for redundancy. Each individual gateway is expected to have a lifetime of over twelve years.

Nonrecurring costs are expected to range from three to seven times the cost of the first gateway, although a nonrecurring factor of five times the cost of the first gateway is assumed for the purposes of this study. Production costs for each gateway are expected to follow a 95% learning curve slope for less than ten antennas, and 90% for systems utilizing ten or more. The estimated number of gateways and antennas, along with their associated costs, are provided in the following table.

Table 7-10 Estimated Gateway Costs for the Modeled Systems

Ground Segment Characteristics	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
Number of Gateways	30	28	6	6	3
Number of Antennas per Gateway	4	5	5	5	2
Gateway T1 Cost ($M FY94)	6	7.5	12.5	12.5	10
Total Gateway Costs ($M FY94)	137	164	128	128	78

7.6 PSTN Interface Costs

Electronics required to interface the gateway baseband signals with the PSTN are generally available in individual blocks, or racks, based on voice channel capacity [Lovell, 1995]. These PSTN connections are expected to have a recurring cost of $1.5 M for every block of 400 voice channels. An initial block of 400 voice channels was required for each gateway site to come online prior to

IOC. After the initial 400 blocks have been purchased for each system, fractions of the 400 voice channel blocks can be added as traffic demand warrants.

The maximum number of PSTN blocks required at each gateway site per year was estimated in the manner described in the system capacity chapter. While estimating the number of users that could be satisfied by each system, the capacity simulation also kept track of the maximum number of instantaneous voice channels processed per gateway site per year. Since the gateway site was disabled for the LEO-66 system, its required yearly PSTN circuits were estimated by keeping track of the maximum number of instantaneous, billable minutes experienced throughout each year. Since the crosslinks allow the system to route calls through other satellites before connecting with the PSTN through a gateway site, this assumption should yield reasonable results. The actual number of individual channels is compiled in the following table.

Table 7-11 Total Number of PSTN Connections Required per Year to Satisfy Estimated Number of Billable Minutes.

NUMBER OF PSTN CIRCUITS REQUIRED PER YEAR										
	10% MARKET SHARE					30% MARKET SHARE				
Year	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
2000	0	0	0	0	0	0	0	0	0	0
2001	203	11200	2400	2400	1200	607	11200	2458	2481	1200
2002	486	11200	2400	2400	1200	1457	11620	3844	4469	1750
2003	1015	11206	3035	3321	1393	3040	14846	6856	8792	3644
2004	1624	11859	4229	4927	1948	4834	20555	9508	13108	5826
2005	2276	13167	5567	6742	2727	6640	26358	11208	16994	8162
2006	2954	14618	6738	8566	3548	8350	31569	12643	19914	10576
2007	3510	16102	7713	10036	4260	9587	35119	13758	22191	12609
2008	3931	17443	8431	11146	4839	10489	37888	14450	23838	14233
2009	4333	18811	9213	12305	5458	11485	40896	15317	25491	15946
2010	4515	19442	9559	12834	5759	11945	42342	15660	26256	16719
2011	4596	19740	9722	13069	5895	12092	42903	15826	26590	17064
2012	4597	19763	9713	13082	5893	12098	42974	15826	26573	17064

7.7 Operations

Operation costs to operate and maintain each system were estimated using predicted manpower requirements. Manning requirements for each gateway

site were estimated at four five-person shifts, while the control center staffing was estimated at four twelve-person shifts [Gumbert, 1995]. The total cost to support each individual staff member, including overhead, was estimated at $150,000 per year [Lovell, 1995]. Operations costs were assumed to start accumulating the year of the first satellite launch. The resulting estimated yearly operations costs for each of the modeled systems is provided in the following table.

Table 7-12 Estimated Yearly Operations Costs for Each of the Proposed Systems.

MODELED SYSTEMS	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
Number of Gateways	30	28	6	6	3
Year of First Launch	2000	1999	2000	2000	2000
Yearly Operations Costs ($M)	97.2	91	25.2	25.2	16.2

Although it is recognized that the cost of control centers should also be incorporated into the total system cost estimates, the network control center costs were not estimated due to the lack of detailed technical information from the proposed systems, as well as the lack of an adequate model to estimate their costs.

7.8 Overview or Summary of System Costs Here

Table 7-13 provides a summary of the $77K/kg satellite cost estimates, along with all of the other estimates, for each of the modeled systems.

Table 7-13 Estimated System Cost Breakdown for the Modeled Systems.

MODELED SYSTEMS	LEO-66	LEO-48	MEO-12	MITMEO-12	GEO-3
1st Generation Satellites	$1,666.3	$720.0	$1,194.5	$1,154.8	$1,351.2
1st Generation Launch	$950.0	$370.0	$455.0	$700.0	$440.0
1st Generation Launch Insurance	$457.8	$191.1	$272.0	$315.0	$228.3
Gateways	$137.3	$164.0	$128.2	$128.2	$77.7
2nd Generation Satellites	$937.3	$409.9	$0.0	$0.0	$0.0
2nd Generation Launch	$950.0	$370.0	$0.0	$0.0	$0.0
2nd Generation Launch Insurance	$377.5	$156.0	$0.0	$0.0	$0.0

In order to enable the derivation of the cost per billable minute metric, the total system costs will need to be spread out over the years that the costs will actually be incurred. In order to model the two generation deployment scheme, the costs will be spread separately for each of the satellite generations. Figure 7-3 displays the total first generation cost breakdown for each of the modeled systems.

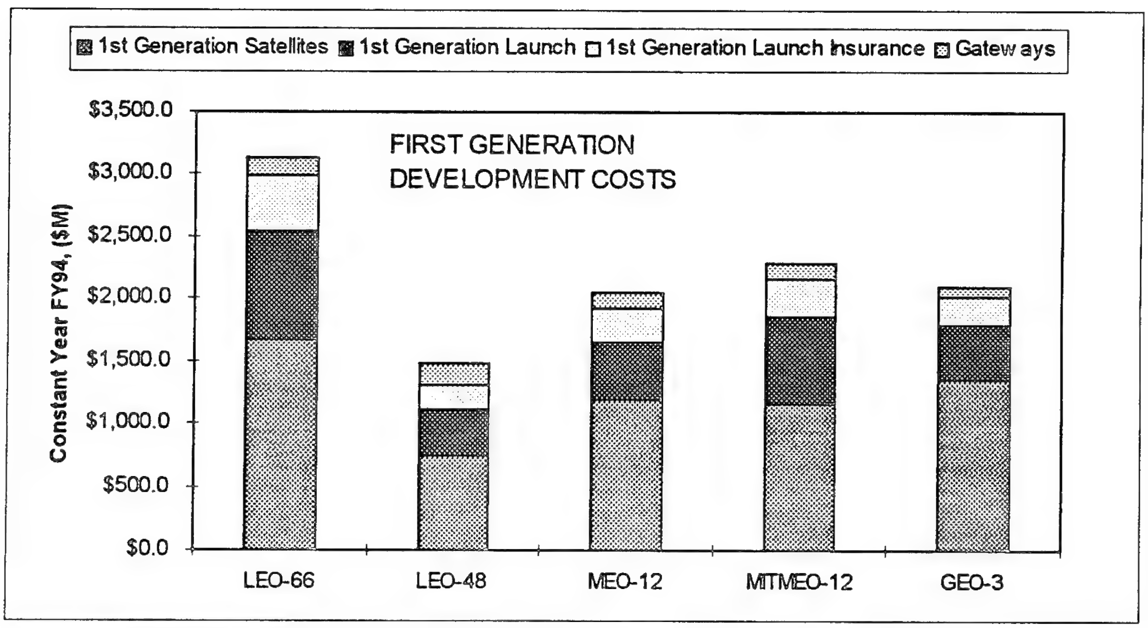

Figure 7-3 Total First Generation Costs for the Modeled Systems.

As expected, the highly complex LEO-66 system requires the largest investment to deploy its first generation system. The two MEO systems and the GEO system appear to require comparable first generation costs, while the LEO-48 system comes in the lowest in cost. The satellite costs dominate the cost results,

followed by the launch and insurance costs. The gateway costs do not appear to significantly affect the total system costs, even for the LEO systems that require the most gateway sites to provide global services.

Figure 7-4 displays a similar plot covering the estimated second generation system costs.

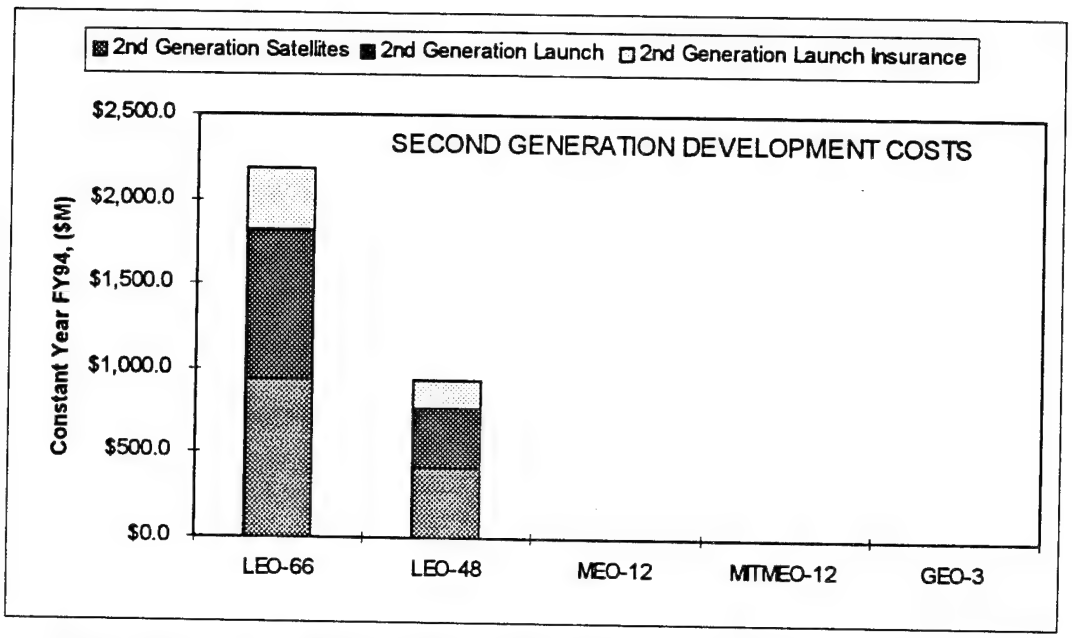

Figure 7-4 Total Second Generation Costs for the Modeled Systems.

The LEO-66 system again comes in much higher than the LEO-48 system, and the second generation costs for the MEO and GEO systems are zero since their first generation is assumed to operate over a full twelve-year lifetime.

The next chapter will take the total first and second generation costs developed in this chapter, and spread them over a reasonable time period to estimate the yearly cost of the system. The spread development costs, combined with the operations and PSTN costs, will be integrated with the billable minutes estimated in chapter 6 to derive the cost per billable minute metric and complete the comparison.

8. Cost per Billable Minute

8.1 Cost Spreading

The models utilized in the previous chapter provide total cost estimates for various aspects of the system. In actuality, each of these costs will be expended over a range of years. In order to determine the total cost of the system for each year of the mission, it is necessary to spread the expended costs over time.

An analytical method to spread costs, based on the experience of actual programs, was developed by Wynholds & Skratt [1977]. The following function represents the approximate the spreading of program costs over the system lifetime:

$$F(S) = A\left[10 + S\left((15 - 4S)S - 20\right)\right]S^2 + B\left[10 + S(6S - 15)\right]S^3 + \left[1 - (A + B)\right](5 - 4S)S^4 \tag{8-1}$$

where S represents the fraction of the development time elapsed, F(S) is the fraction of cost consumed in that time, and A and B are empirical coefficients that vary depending on how the costs are loaded over time. Wong suggests assuming approximately 60% of the development costs of a satellite system will be expended by the midpoint (S=0.5) of development if either one or two satellites are being developed [Wong, 1992]. If more satellites are developed, the 60% decreases towards a limit of 50% [Wong, 1992]. Table 8-1 displays the

relationship between the coefficients A and B, and the percentage of system costs expended at the midpoint of development [Wong, 1992],

Table 8-1 Cost Spreading Equation Coefficients.

% Expenditure at Midpoint of Development	A	B
80	0.96	0.04
60	0.32	0.68
50	0.00	1.00
40	0.00	0.68
20	0.00	0.04

An analysis of the proposed cost schedules from the Iridium, Globalstar, and Odyssey refilings in November 1994 matches closely with the assumption of a 50% expenditure at the midpoint of development. The Globalstar and Odyssey cost schedules each projected a 48% expenditure level, while the Iridium system displayed a 30% expenditure level at the midpoint of development. The Iridium percentage should be considered carefully, however, since the published costs do not adequately represent the costs borne by all the partners in the Iridium program. Indeed, "some major suppliers, such as Lockheed Corp. ... and Raytheon Co. ... worked with Iridium ... without contracts or payment for over two years in order to bring the project to fruition" [Kinni, 1994]. It is likely that if all the hidden costs were included in the calculation, the Iridium expenditures would approach 50% at the development midpoint. This study assumes a 50% level for the cost spreading of each system.

The development, production and deployment costs of the two satellite generations were spread separately. First generation costs, including satellite, launch vehicle and gateway development costs, were spread over a six year period ending in the year 2000 when each system becomes fully operational. Iridium has claimed a seven year development time, while the Globalstar and Odyssey filings have each projected development will occur in six years. First generation costs were spread over a six year period due to the FCC requirement

that all licensed systems begin service by the sixth year of their license. The second generation of the two LEO systems was spread over a four year period, ending with the last launch of the second set of satellites, occurring six years after the final launch of the first generation. Second generation costs include the costs to develop and launch a second set of operational, on-orbit, and ground spare satellites, as well as the continuing operations and PSTN costs. The shorter spreading period represents the shorter time required to produce a second block of satellites.

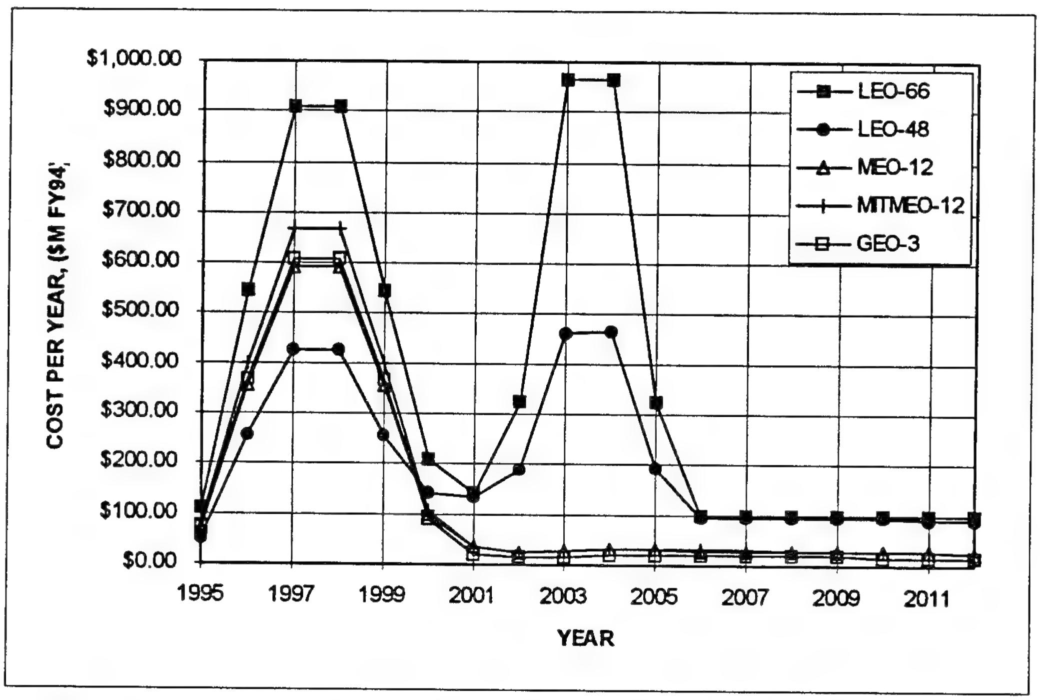

Figure 8-1 Spread System Costs for the 10% Market Penetration Case

Each system's spread costs for the 10% market penetration case are displayed in Figure 8-1. The two large peaks beginning in 1997 and 2003 represent the midpoint of development for the two generations of satellites. The MEO and GEO systems exhibit a single peak since they require a single satellite generation to provide service over a twelve year period. The peaks for the second generation LEO systems appear higher since they have been spread over a

shorter time period. The low costs seen after the main peaks and continuing until 2012 represent the yearly operations costs, and the costs to add additional PSTN circuits at the gateways as the market demand warrants.

A similar plot of the spread costs for the 31% market penetration case is portrayed in Figure 8-2. Although the two plots appear nearly identical, the main difference lies in the number of additional PSTN circuits required to satisfy a larger percentage of the market. Other than that difference, the satellite, launch vehicle and operations costs are identical to the 10% market penetration case.

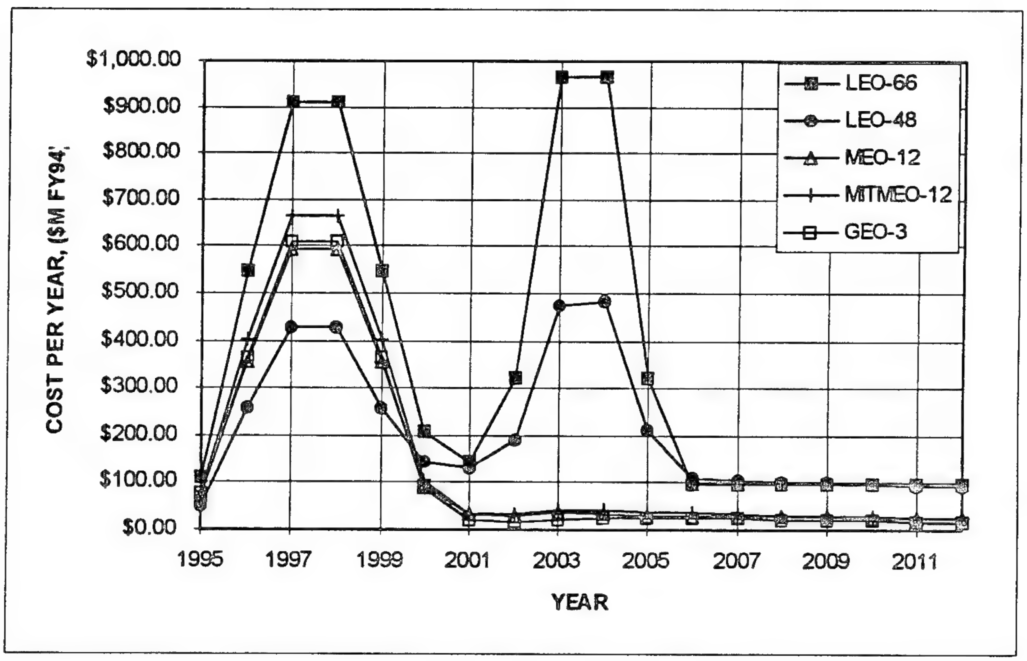

Figure 8-2 Spread System Costs for the 31% Market Penetration Case.

8.2 Integration of Cashflow

The estimated costs have to be spread over the development period due to the "first law of finance. Simply stated, *A dollar today is worth more than a dollar tomorrow*" [Dickerson, 1995]. The reason for this is that a dollar today can be

invested so that it will have earned interest by tomorrow. The corollary to this is that the money expended on system development later in the mission effectively costs less than the same amount of money spent today. The mathematical relationship describing this effect is referred to as the net present value (NPV) [Dickerson, 1995]. Imagine $1.5 M are to be spent ten years from now to construct a gateway terminal in the Australian outback to provide mobile service to Australia's rapidly expanding population. The present value (PV) of that money can be calculated as follows:

$$PV = \frac{FV}{(1+k)^n} \tag{8-2}$$

where FV represents the future value of the money, n represents the number of years covered by the investment, and k represents the rate of return, or interest rate expected on the investment. In our case, if the gateway costs $1.5 M, and the local bank has been offering 10% interest in its passbook account, the present value of the investment 10 years from now is

$$PV = \frac{\$1.5M}{(1+0.1)^{10}} = \$578K \tag{8-3}$$

or less than half the total cost of the gateway. If the systems designer had instead decided to build the gateway terminal today thinking the market in the outback was going to suddenly expand, the company would have lost $922 K, because an investment of only $578 K today could have covered the costs of the $1.5 M gateway in ten years. In other words, the "present value of any future sum is the amount that must be invested today in order to provide that future amount" [Dickerson, 1995]. This process of translating future expenditures into equivalent present values is referred to as discounting.

Due to the time value of money, the expected costs (outflow) and revenues (inflow) for each year of the mission will need to be discounted separately to determine their present value. The usual nomenclature is to consider revenues as positive since they flow into the company, and costs as negative since they flow out of the company. This collection of numbers is called a cashflow and represents the annual net flow of cash through the system for every year of the mission [Dickerson, 1995]. Since the cashflows will be used to evaluate different systems, and taxes are not involved, depreciation is not considered. Other costs excluded from the cashflows in this study include costs due to marketing, sales, billing, administration, finance, human resources and customer service. Although these elements will certainly add to the cost of each system, they are not expected to vary much between different system architectures, but would instead be dependent on the companies involved.

The NPV of the total system can now be expressed as a sum of the NPV of the inflows and the outflows for every year of the mission,

$$PV_{system} = \left(\sum_{i=1}^{n} \frac{CF_i}{(1+k)^i} \right)_{revenue} - \left(\sum_{i=1}^{n} \frac{CF_i}{(1+k)^i} \right)_{costs} \tag{8-4}$$

where CF_i represents the cashflow, cost or revenue, flowing through the company in year i, n represents the period of expenditures (18 years in the study), and k represents the expected rate of return. Equation (8-4) assumes that all cashflows occur at the end of the year. The yearly revenue $(CF_i)_{revenue}$ of the system can be determined by multiplying the number of billable minutes provided per year, N_{BM_i} by the equivalent revenue received from each minute, or the cost per minute, C_{min}:

$$(CF_i)_{revenue} = C_{\min} N_{BM_i} \tag{8-5}$$

The final parameter required in equation (8-4) is the expected rate of return. Before a bank or large investor considers a long term investment in an expensive and risky aerospace venture such as a mobile satellite system, they generally require evidence that the system has the capability to return 30% over the value of the original investment [Lovell, 1995]. The discount of rate of 30% should thus be used to compute the present value of the future costs of the system. Although inflation can be expected to decrease the value of the cash flows in the future years, the rate of return is assumed to include all of the risks faced in the investment, including the decrease in purchasing power of the dollar [Dickerson, 1995].

Now that all of the variables have been defined, one final step is required to compute the cost per billable minute. One of the main methods used to evaluate and rank different projects is the internal rate of return (IRR) [Dickerson, 1995]. This method involves determining the specific discount rate that forces the project's net present value to equal zero" [Dickerson, 1995], or equivalently,

$$PV_{system} = \left(\sum_{i=1}^{n} \frac{C_{\min} N_{BM_i}}{(1+IRR)^i} \right)_{revenue} - \left(\sum_{i=1}^{n} \frac{CF_i}{(1+IRR)^i} \right)_{costs} = 0 \tag{8-6}$$

Since the IRR has already been set at 30% in order to attract investors, the only variable in the equation is the cost per minute. Equation (8-6) can be rearranged in order to estimate the cost per billable minute required to achieve a 30% IRR:

$$C_{\min} = \frac{\left(\sum_{i=1}^{n} \frac{CF_i}{(1+IRR)^i}\right)_{costs}}{\left(\sum_{i=1}^{n} \frac{N_{BM_i}}{(1+IRR)^i}\right)_{revenue}} \tag{8-7}$$

8.3 Cost per Billable Minute Results

Equation (8-7) was used to estimate the cost per billable minute achieved by each of the model systems when allowed access to 10% and 31% of the expected market. Figure 8-3 displays the results of the cost per billable minute comparison using the $77K/kg satellite cost model.

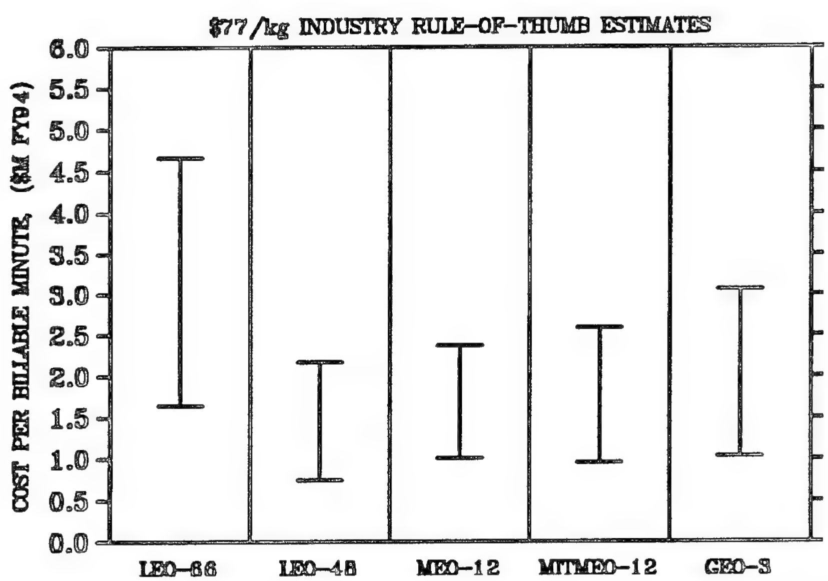

Figure 8-3 Estimated Cost per Billable Minute Using the $77K/kg Satellite Cost Model.

The results indicate that the lowest cost per billable minute results, ranging from 75 cents (31% penetration) to $2.17 (10% penetration) a minute, are achieved by the LEO-48 system, which is modeled after the Globalstar system. Whether provided access to 10% or 31% of the total market, the LEO-48 system requires the least cost per billable minute to achieve a 30% rate of return. The highest

cost per minute system, on the other hand, is shown for the other LEO system, LEO-66, which is modeled after the Iridium system. LEO-66 shows cost per minute results ranging from $1.60 to $4.50 per minute. The other systems fall in the middle, showing cost per billable minute results comparable to, but slightly higher than, the LEO-48 system. Both of the MEO systems and the GEO-3 system display higher cost per billable minutes than LEO-48 at the 10% penetration rate, but achieve quite comparable results at a 31% market penetration. At 10% penetration, the cost per minute results seem to generally scale with the altitude of the system, if LEO-66 is excluded.

Figure 8-4 and Figure 8-5 display the cost per billable minute results for the two Space Command cost models. Although the results from the USCM7 models show similar trends, they should be interpreted with caution for the GEO-3 results since the dry mass of the satellite was well beyond the recommended range of the models.

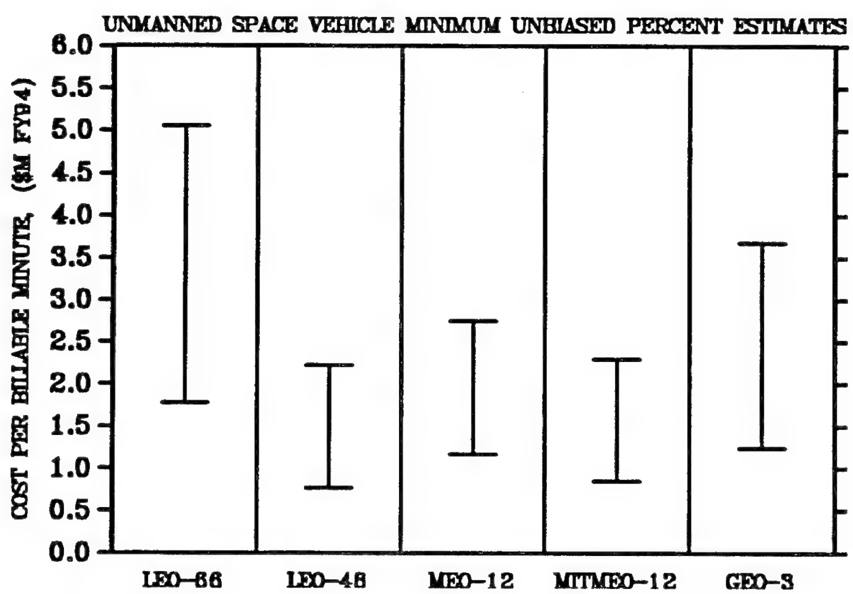

Figure 8-4 Estimated Cost per Billable Minute Using the USCM7 Minimum Unbiased Percent Error Cost Model.

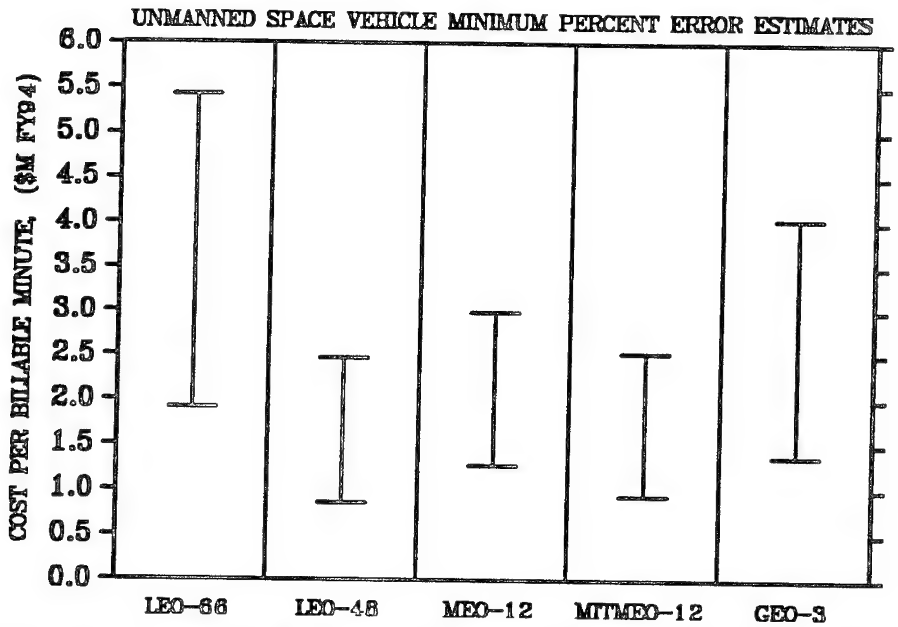

Figure 8-5 Estimated Cost per Billable Minute Using the USCM7 Minimum Percent Error Cost Model.

It is important to note that the cost per billable minute reported in this thesis does not represent an estimate of the actual charge to the consumer. Instead, it represents the cash per minute required to flow back into the company in order to achieve a 30% rate of return. In that sense, the cost per billable minute can be considered an absolute minimum charge, although individual systems could sacrifice revenue in the early years by charging less, in order to achieve higher penetration of the market.

Even though the LEO-66 system appears to require a much higher cost per billable minute for similar penetration rates, it could still provide a comparable, or even superior, cost per minute if it achieves a higher percentage of the market. Market penetration thus appears to be a more important driver of the cost per minute than the actual system architecture, as long as the system design provides comparable service to the other systems. Market penetration will be determined by many different factors, including the marketing scheme, the quality of service, the financial capabilities of the individual company, and international clout of the individual companies. This is why the Big LEO

companies in the United States have been fighting against Inmarsat to keep it out of the international handheld MSS market. They are concerned that because "Inmarsat members operate as monopolies on their national territories" they will be able to "lock out Inmarsat-P competition" [de Selding, 1994]. In addition, Inmarsat may have an additional advantage as "it has international operating agreements to provide service to countries around the world where its investors are based" [*Satellite News*, Jan. 1995]. This sensitivity to the level of market penetration achieved explains why the applicants have been scrambling to create partnerships and find investors with companies around the world. It also explains why being first to market can be an important advantage. If the first system to market is able to achieve a significant fraction of the available market, it may be difficult for other systems that are comparable in quality to catch up.

9. Conclusions

Many companies have proposed to augment terrestrial cellular coverage throughout the world using satellite networks capable of providing communication services to mobile handheld terminals. Although the architectures proposed for these systems vary considerably in their selection of satellite constellations, payload design and network architectures, the success of each design approach will depend primarily on how cost effectively they can provide communication services to the expected market.

Using the results of an extensive market study, a market model has been developed to estimate the size of the addressable market from 2001 to 2012. The model includes regional and time-of-day variations, and takes into account the expansion of terrestrial cellular systems. Although optimism abounds regarding the size of the expected market, with potential revenues projected as high as $17 billion in 2003 [Herring, 1994], it is certainly possible that the market will not grow as much or as quickly as anticipated. Satellite systems designed to operate in a large market may be poorly equipped to provide cost effective service in a smaller market. Thus, the effectiveness of five different mobile satellite system architectures has been evaluated, based on their ability to satisfy 10% and 31% of the expected market. The cost effectiveness of the modeled systems has been evaluated based on a cost per billable minute metric. This metric reflects the cost per minute of service that must be recovered by the system to achieve an internal

rate of return of 30%. The two main segments of the metric include the system's effective, or billable, capacity and its development and operations costs over the twelve year mission lifetime from 2001 to 2012.

The billable capacity for each of the architectures, a direct measure of a system's potential revenue, has been estimated using an extensive computer model. The developed model estimates how much of the addressable market a given system is able to satisfy by considering many different design constraints limiting the usable system capacity. These constraints include mutual view considerations between the satellites, users and gateway antennas, market penetration, bandwidth limits on the mobile and feeder links, overall system availability due to fading and multipath considerations, interference limits for CDMA systems and limits on both the available RF power on the satellites and maximum power flux density on the ground. The effective capacity of each system has been determined when allowed access to 10% and 31% of the expected market. The total lifecycle costs of each system have also been determined for both market penetration cases. The costs include development costs for the satellites, launchers and gateways, launch insurance costs, PSTN connection costs, and operations costs for the gateways and control centers.

The remainder of this chapter will summarize the major results of this study, outline a few other issues likely to affect the success of proposed mobile satellite systems and discuss the final conclusions.

9.1 Overview of Results

The billable capacity results indicate that all of the systems are capable of providing communication services to handheld terminals. In addition, there appears to be room for multiple systems since none of the systems are able to fully satisfy the expected market at either 10% or 31% penetration of the market. Although the effective capacities of all the systems are comparable for the first

few years of the market, the systems diverge as the market begins to grow. The two MEO systems achieve the highest effective capacities at 10% market penetration, but are overtaken by the two LEO systems when the market penetration is increased to 31% of the expected market. This result suggests that the LEO systems may have a greater potential for future growth. The GEO-3 system provides the lowest effective capacities at 10% market penetration levels due to the poor link availabilities provided at higher latitudes. At 31% market penetration, however, the effective capacity of the GEO-3 system surpasses the effective capacity of the MEO-12 system due to limits on MEO-12's available power.

The total lifecycle costs were found to be comparable for all of the modeled systems except for LEO-66, which was determined to be the most expensive system to deploy and operate over the twelve year system lifetime.

All systems are shown to provide cost effective services when addressing 31% of the expected market. Despite the differences in total cost and billable capacity, the cost per billable minutes for all of the systems, excluding LEO-66, appear comparable at this level of market penetration. When only allowed access to 10% of the expected market, the cost per billable minutes achieved by the various systems begins to approach current Inmarsat rates as depicted in Figure 1-1.

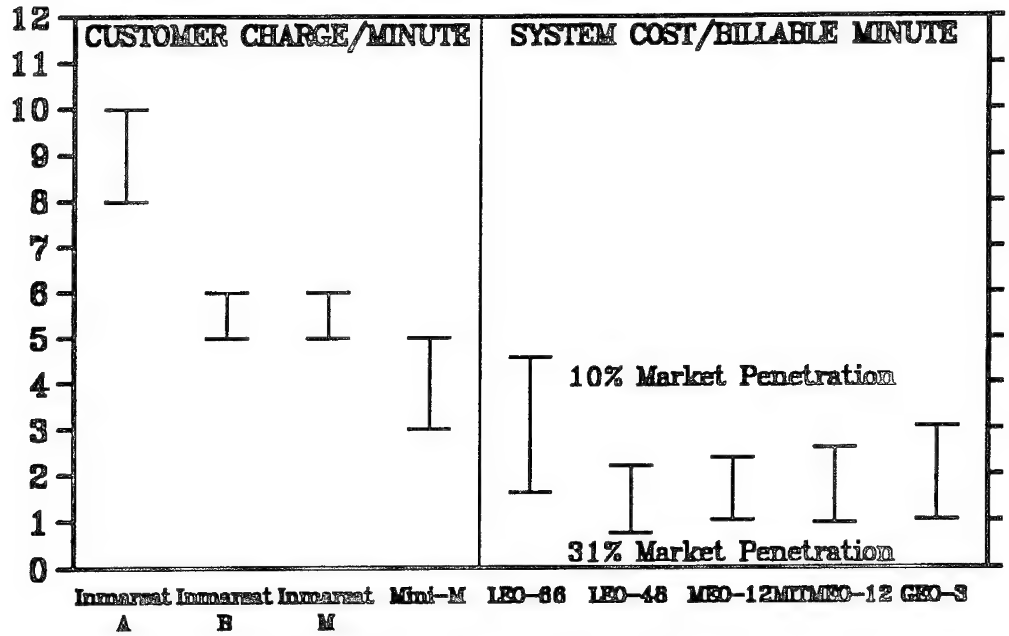

Figure 9-1 Modeled Cost per Billable Minute Results vs. Current Inmarsat Charge per Minute Rates.

Although the current Inmarsat services are not of comparable quality, the addressable market available to the Big LEO providers will be greatly reduced if their charge per minute of service begins to exceed the current Inmarsat rates. It is important, however, to emphasize that the cost per billable minute reported in this thesis does not represent an estimate of the actual charge to the consumer. Instead, it represents the cashflow from each minute of service that must flow back to the company so that it may achieve an internal rate of return of 30%. Thus, the cost per billable minute may be interpreted as a lower bound on the cost to the consumer, although a system could decide to sacrifice revenue in the early years by charging less, in the hopes of achieving a higher market penetration.

In both cases, the system modeled after Globalstar, LEO-48, provides the most cost-effective service, while the system modeled after Iridium, LEO-66, requires the highest cost per billable minute. The cost per billable minute results, however, are shown to be very dependent on the level of market penetration achieved, indicating that other factors such as marketing strategy, quality of

service, available capital and access to foreign markets will become the dominating determinant. Even though the LEO-66 system appears to require the highest cost per billable minute at similar market penetration levels, it could still provide comparable or superior cost per billable minute services if it achieves a higher percentage of the market. Market penetration thus appears have a more significant affect on the cost per billable minute than the actual system architecture, provided the design provides a level of service comparable to the other systems.

Market penetration will be determined by many different factors, including marketing strategy and the financial capabilities and international clout of the system providers. This exemplifies why the Big LEO applicants in the United States have been fighting so hard to keep the new Inmarsat affiliate out of the international handheld MSS market. The concern is that because "Inmarsat members operate as monopolies on their national territories," they will be able to "lock out Inmarsat-P competition" [de Selding, 1994]. In addition, Inmarsat may have an additional advantage as "it has international operating agreements to provide service to countries around the world where its investors are based" [Satellite News, Jan. 1995]. The perception is that these competitive advantages will allow Inmarsat-P easier access to a large percentage of the expected market, which would result in a lower cost of service difficult to beat. In a similar sense, the first system to market may achieve a significant competitive advantage. If the first system to market is able to capture a significant fraction of the available market, it may be difficult for other systems of comparable quality to compete.

9.2 Elevation Angle Coverage

The constellation design for a mobile satellite system can have a profound effect on the quality of the communications service provided to the end user. This relationship is due to the relationship between the elevation angle from the user to the satellite, and the probability that a signal will be blocked. Although a

system that provides a lower average elevation angle can counteract the increased fading level with increased link margin, it is still likely that increased fading, and therefore decreased system availability, will be experienced in some situations and some environments. In addition, the fading calculations discussed in chapter 5 provide a rough estimate of the average system availability by estimating the probability of signal blockage using the centroid slant range, and averaging over three different environments. The coverage statistics of a constellation can thus provide some indication of how likely the system availability may be reduced in some situations due to poor elevation angle coverage.

A separate simulation was run to determine the constellation coverage statistics for each of the modeled systems. These statistics are dependent on the elevation angle, ε, coverage provided on the ground. This elevation angle can be estimated from

$$\varepsilon = \frac{\pi}{2} - \cos^{-1}\left(\frac{\vec{R}_{site}}{R_{site}} \bullet \left(\frac{\vec{\rho}}{\rho}\right)\right) \tag{9-1}$$

where $\vec{R}_{site}$ and $\vec{r}_{satellite}$ are the position vectors of a position on the ground and the satellite in geocentric coordinates, respectively. The vector $\vec{\rho}$ is then determined by $\vec{\rho} = \vec{r}_{satellite} - \vec{R}_{site}$ (Equation (1-1) will return a negative elevation angle if the satellite is below the outer horizon of the ground station).

Figure 9-2 displays the elevation angle coverage provided by the Odyssey constellation for a snapshot in time. The gray scales (the elevation angle is mapped linearly to a 13-color scale ranging from 0° to 90° elevation) superimposed on the world map represent the elevation angle from the position on the ground to the highest satellite in view within the constellation. The

centers of the ovals thus represent the subsatellite points of the twelve satellites in the system.

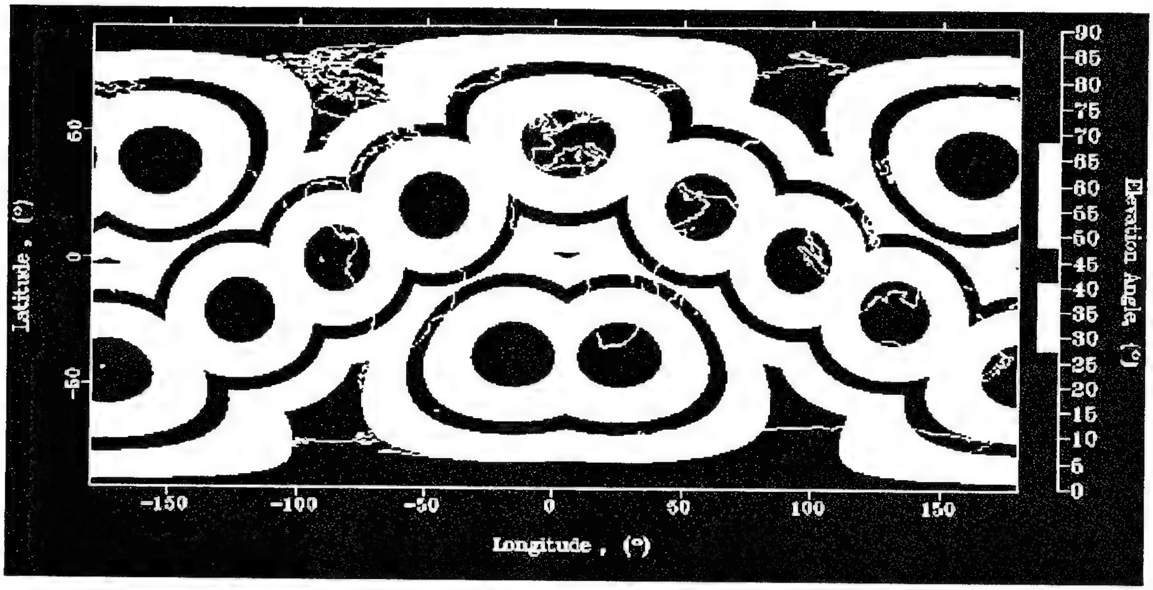

Figure 9-2 **A Snapshot of the Elevation Angle Coverage Provided by the Odyssey System.**

This plot illustrates that the elevation angle coverage provided by the Odyssey system at this instant of time is often over 50°. This coverage, however, will vary as the satellites and the Earth move in their orbits. It is therefore beneficial to look at the elevation angle coverage in terms of statistics.

Figure 9-3 displays the average elevation angle achieved by some of the proposed systems as a function of latitude.

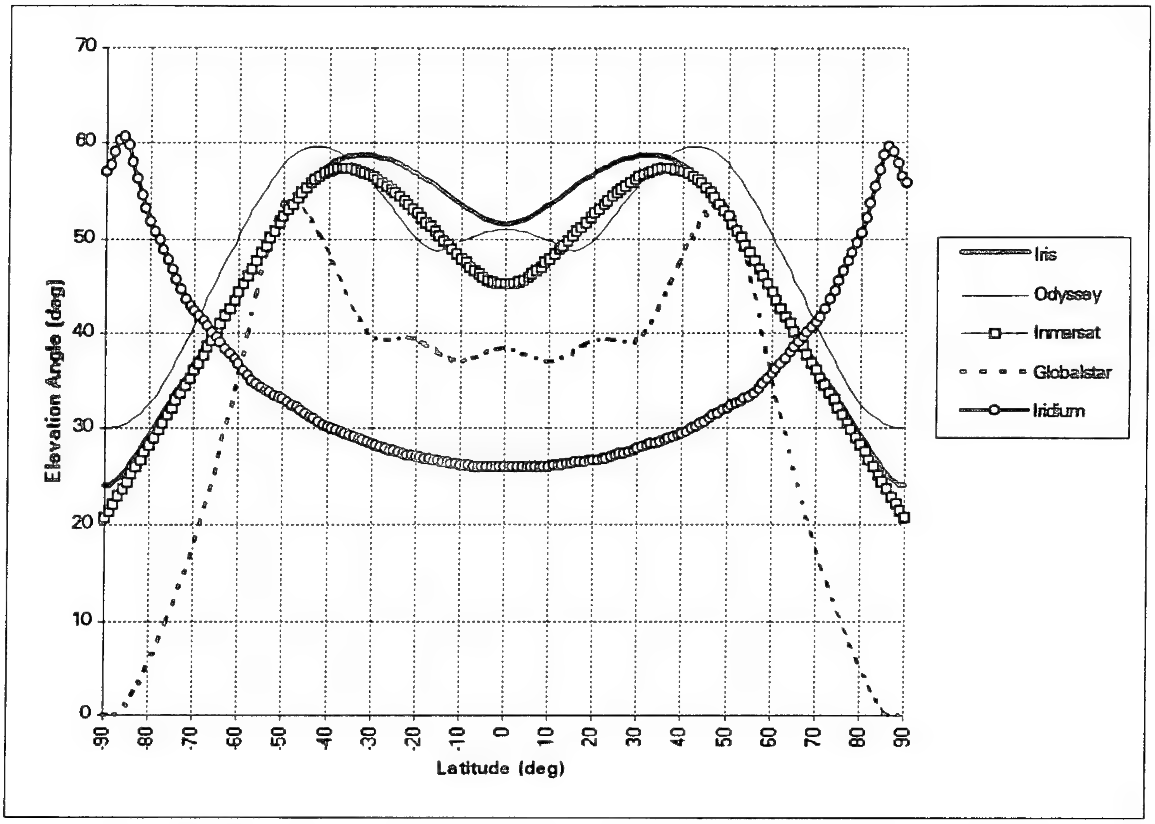

Figure 9-3 Average Elevation Angles for Some of the Proposed Systems.

This figure shows that the three MEO systems provide the best average elevation angles within 60° latitude, although the Globalstar system approaches similar average angles between 40° and 50°. The best average elevation coverage provided above 70° latitude is achieved by the Iridium system, since it utilizes a constellation of polar satellites.

Figure 9-4 provides a similar coverage comparison of the systems by plotting the average number of satellites in view above the minimum elevation angle of each satellite's viewing area as a function of latitude.

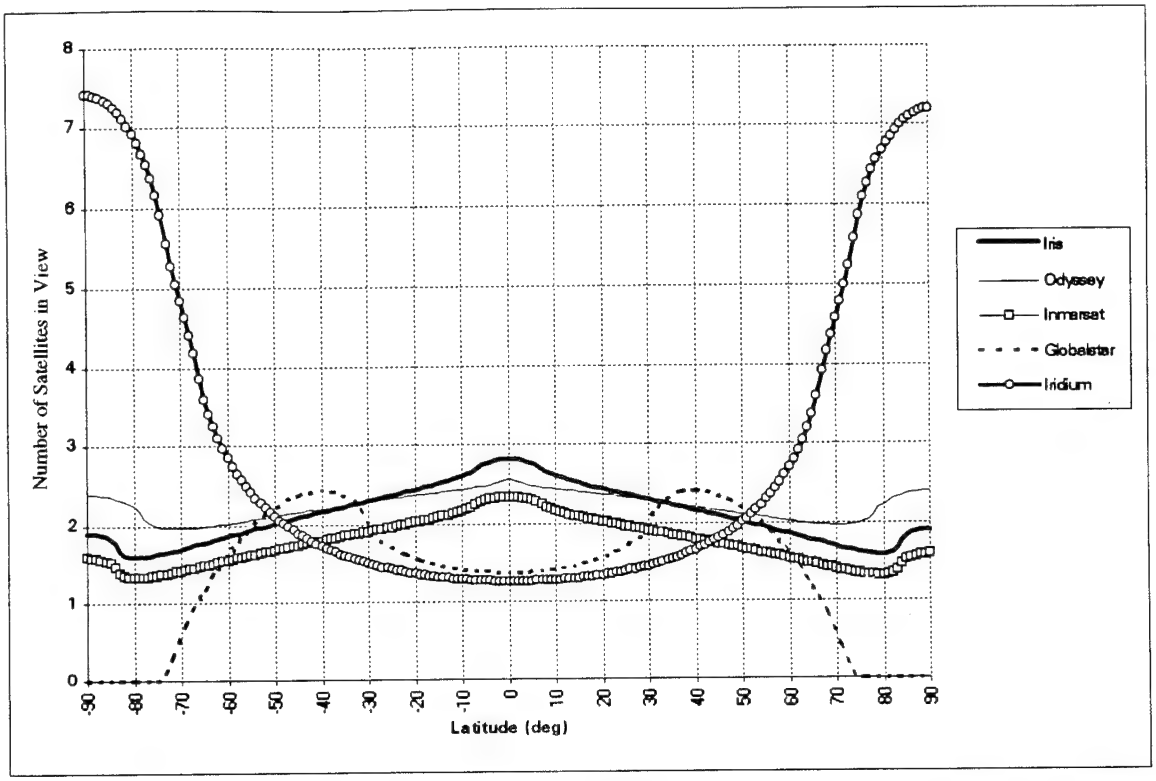

Figure 9-4 Average Number of Satellites in View for Some of the Proposed Systems.

Although the average elevation angle will provide a measure of the availability of a particular satellite in a given environment, there are ways to improve the overall system availability. One of the major methods that can be used is to ensure that multiple satellites are in view to each user. Thus, Figure 1-4 represents another measure of how well a system will be able to provide a reasonable availability in fading environments. As seen in the figure, the MEO systems again provide the best coverage, in terms of the number of satellites in view, by achieving an average of two to three satellites in view within 50° latitude. The Globalstar system achieves similar results between 30° and 60° latitude, while the Iridium system does not achieve an average of two or more satellites in view until above 50° latitude.

Although the number of satellites in view, and the average elevation angle both illustrate certain aspects of the coverage quality well, the best way to look at the

coverage statistics is in terms of the probability that a satellite can be seen within a certain elevation angle range. Figure 9-5 illustrates the elevation angle probability density function for some of the proposed systems.

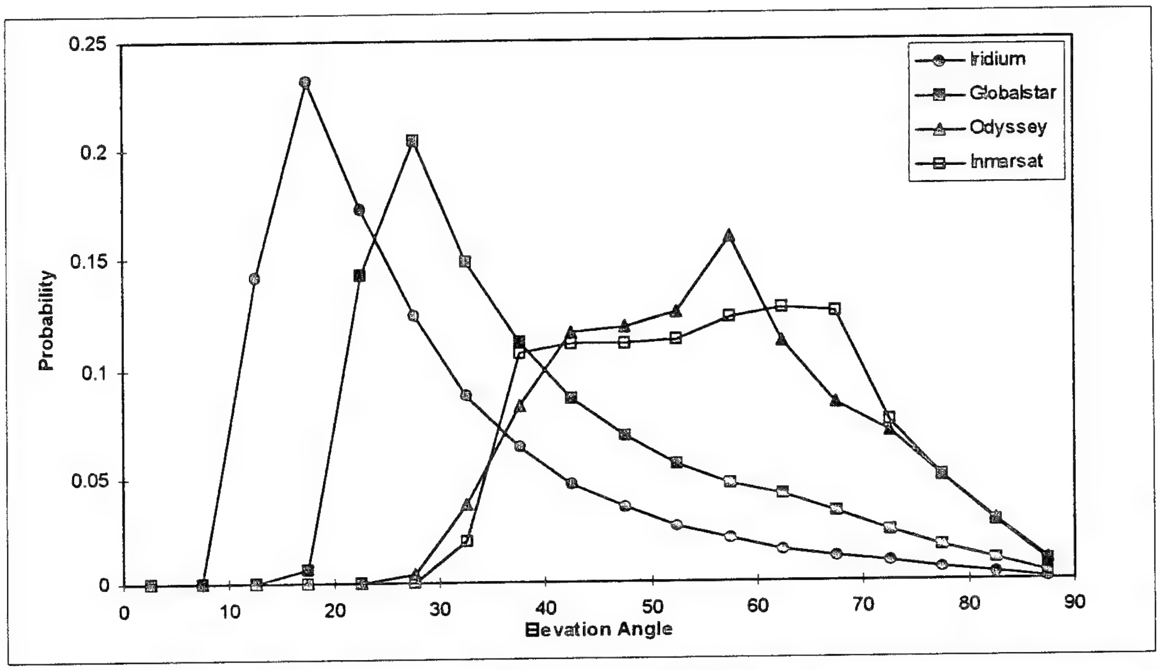

Figure 9-5 **Elevation Angle Coverage Probability Distribution for Some of the Proposed Systems.**

As shown in the figure, the MEO systems provide much better coverage than the LEO systems, with elevation angles between 40° and 70° falling in the most probable range. The Globalstar system most often provides elevation angles between 20° and 35°, while the Iridium system most often achieves angles between 10° and 25°.

In summary, since the market penetration that a system is able to achieve will greatly affect its cost per minute, and since the quality of service is likely to play a large factor in the consumer acceptance of the system, the elevation angle coverage could greatly affect the success of the individual systems. Although the large fading margins required at low elevation angles can be counteracted

with higher link margins, the proposed MEO systems definitely have an advantage when it comes to providing a high quality level, and this advantage could translate into a higher customer acceptance, a higher penetration of the market, and consequently a lower cost per billable minute.

9.3 Conclusions

In summary:

1. The cost per billable minute metric provides a fair and meaningful measure of the cost effectiveness of different mobile satellite systems to provide communication services addressing a specified market. This metric is sensitive to all the major system drivers, and measures how cost effectively the top level requirements are satisfied. Although the metric is useful for the evaluation of different proposed commercial communications systems, it can also be successfully utilized throughout the design process to enable consistent decision making and to measure how different design choices will affect the cost effectiveness of the overall system.

2. A useful tool has been developed that estimates the billable capacity of selected geostationary and nongeostationary mobile satellite communication systems in a specified market. The capacity tool can propagate all of a system's satellites while mapping each spotbeam onto the Earth's surface, and then estimate the number of billable minutes that the system is able to satisfy under a range of constraints, including bandwidth limits, uplink interference limits, power flux density limits, and available RF power limits. Other capacity constraints include ensuring the visibility of an available gateway antenna and limiting the billable capacity to the available traffic.

3. All systems appear technically capable of providing mobile voice services to handheld terminals.

4. Room exists in the market for multiple systems since reasonable cost per billable minute results are achieved by each system when allowed access to only 31% of the expected market.

5. Mobile satellite communication systems may not prove profitable in a greatly limited market since the cost per billable minute achieved by each system begins to approach current Inmarsat rates at 10% market penetration levels.

6. The lowest altitude system, LEO-66, requires the largest overall investment to deploy and operate over a twelve year lifetime due to the large number of relatively complex satellites. This system architecture does not appear to provide competitive cost per billable minute results in a limited market, although it may prove more successful at higher market levels.

7. GEO systems suffer from significant time delays that could potentially decrease consumer acceptance. Although user reaction studies have indicated varied results, most people agree that the long delays associated with a double hop preclude mobile-to-mobile traffic for GEO systems. Despite the fact that Inmarsat provides mobile voice services from GEO to many customers, it is uncertain how many users would find the delay unacceptable when provided with lower time-delay solutions at a similar cost of service.

8. MEO systems provide the best overall elevation angle coverage of all the systems within 70° latitude. This better coverage will provide them with a potential service quality advantage over the other systems since the probability of signal fading and blockage is especially dependent on the elevation angle, although LEO systems may be able to partially counteract the large fading levels expected at lower elevation angles by supplying higher link margins and providing multiple satellites in view to the user.

Although this thesis has provided a number of interesting conclusions, the results obtained from any study are a reflection of its assumptions. Future studies could improve the results obtained here by further exploring a number of aspects of the traffic model, capacity model and cost estimates.

The addressable market model utilized in this study assumed a uniform density of users within each 15° by 15° traffic grid, and assumed no seasonal variations in the yearly traffic. Including seasonal variations would provide a more accurate model that could further highlight systems that are operating close to their capacity limits. Non-uniform traffic grid distributions, on the other hand, could simulate the effect of increased traffic demand from individual cities.

Although adding details to the traffic model will provide a more realistic simulation of the situation, modifying the capacity and cost assumptions could

have a much greater affect on the overall results. The major assumptions in the system capacity simulations that could most significantly change the cost per billable minute results include the fading and power control assumptions. Although fading and blockage effects are expected to play a major role in the systems availability and voice quality provided by mobile satellite systems, this study utilized a very simplified fading model based loosely on some results found in the literature. Future studies could develop more sophisticated models of fading and blockage that more accurately predict the maximum and average fading levels expected in a given environment and at a specified elevation angle. In fact, Vogel has suggested that an empirical model applicable over a range of environments may be available within the next year [Vogel, 1995]. The other major assumption, that each of the systems could provide power control within 2 dBW per user, could also have a significant affect on the effective capacity of each system. In particular, the longer time delays at MEO and GEO make it more difficult to accurately power control using a closed loop feedback system. If any of the systems are unable to power control within 2 dBW, the effective capacity of the system could be drastically reduced [Rusch, 1995], and the resulting cost per billable minute could be correspondingly increased.

Assumptions made in the cost analysis could also greatly affect the results of the study. The individual cost estimates that could be improved the most include the launch costs, gateway costs, control center costs and operations costs. The launch costs could be improved by obtaining actual quotes from the various launch providers, and utilizing more detailed launch insurance rates for each of the boosters. The gateway and operations costs, on the other hand, could be improved by obtaining more detailed cost models. A few gateway cost models were found that are available for use in the Defense Department or NASA, although most of them were considered proprietary. Other gateway cost models and control center cost models may be available within the industry. A recent

model to predict operations costs for a variety of satellite missions has become available this summer, however [Carraway, 1994; Boden, 1995].

Although adding more detailed models will improve the overall fidelity of the cost analysis, the most significant factor affecting the accuracy of system cost estimation has been shown to be the choice of a learning curve rate [Book, 1995]. As an example, if a 90% learning curve rate is assumed to estimate the production cost of 50 satellites, and the actual learning rate turns out to be 95%, the actual costs will exceed the estimate by 36% [Book, 1995]. The results obtained here assuming an 85% rate for the LEO systems, 90% rate for the MEO systems and 95% rate for the GEO system could change significantly if the learning curve rates are changed. Thus, further study should investigate the sensitivity of the cost per billable minute results to the choice of a learning curve rate. It has also been suggested that learning curve theory should not be extended to account for the effects of mass production efficiencies in addition to the standard improvements in management, engineering and production [Burgess, 1995] Instead, it has been suggested that the standard learning curve rate for all satellite programs should be modeled at a 95% rate, and the decreased costs due to mass production efficiencies should instead be modeled using a rate adjustment curve [Burgess, 1995]. Further analysis should incorporate a production rate adjustment curve into the cost estimation.

Time constraints and computing limitations restricted the number of MSS architectures that could be evaluated as part of this study. Although the five modeled systems represent a range of different MSS solutions, a number of other architectures have been proposed in the past few years. The Ellipso system in particular offers a unique solution that could possibly provide more cost effective services to the MSS market. Any future work in this area should incorporate other systems, such as Ellipso, into the comparison.

In closing, a model to determine the cost per billable minute for a variety of mobile satellite system architectures has been developed. Although this metric is particularly useful to evaluate the currently proposed Big LEO mobile satellite communication systems, the model could be easily extended to enable the evaluation of the recently proposed high-bandwidth data distribution systems such as Teledesic, Hughes' Spaceway and Loral's Cyberstar, or of the Little LEO, low datarate paging systems such VITASAT, or Orbital Science Corporation's Orbcomm system, by developing a similar metric that combines the total system cost with a unit of communication service provided by normalizing them based on a specified internal rate of return.

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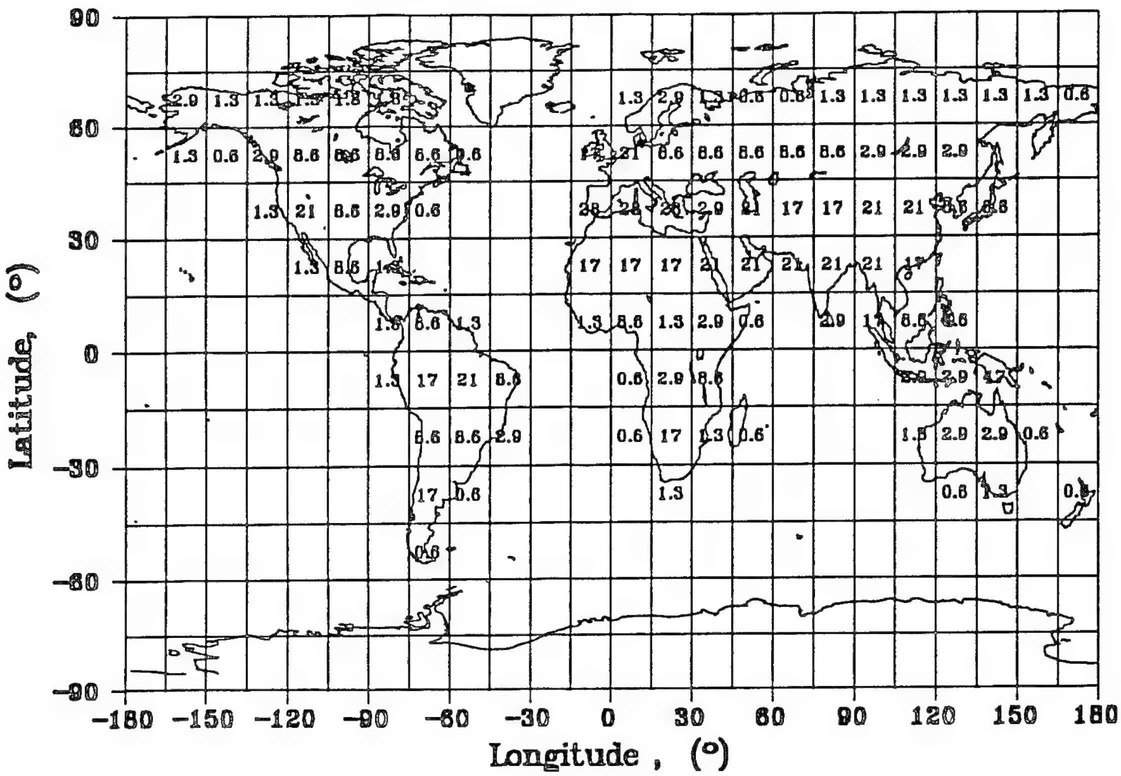
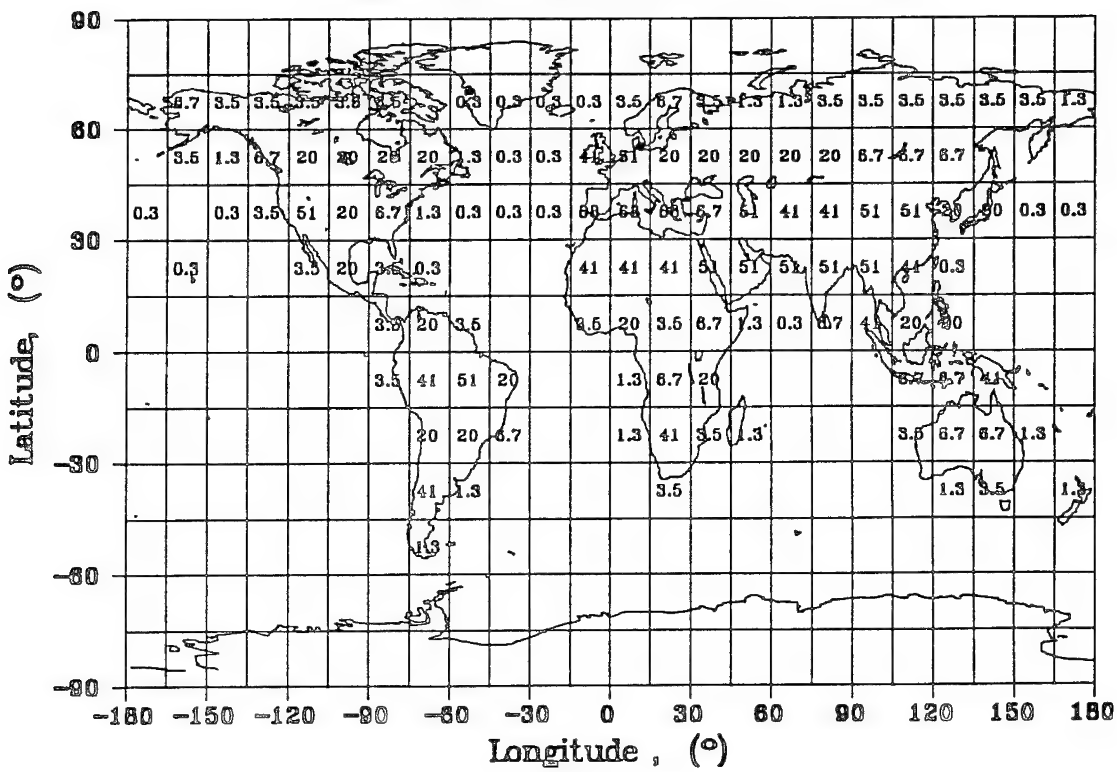
Appendix A: Market Study Maps

This appendix contains the traffic model maps for 100% of the expected market in millions of addressable minutes per year from 2001 to 2012. The traffic maps are binned into 15° latitude and 15° longitude grids.

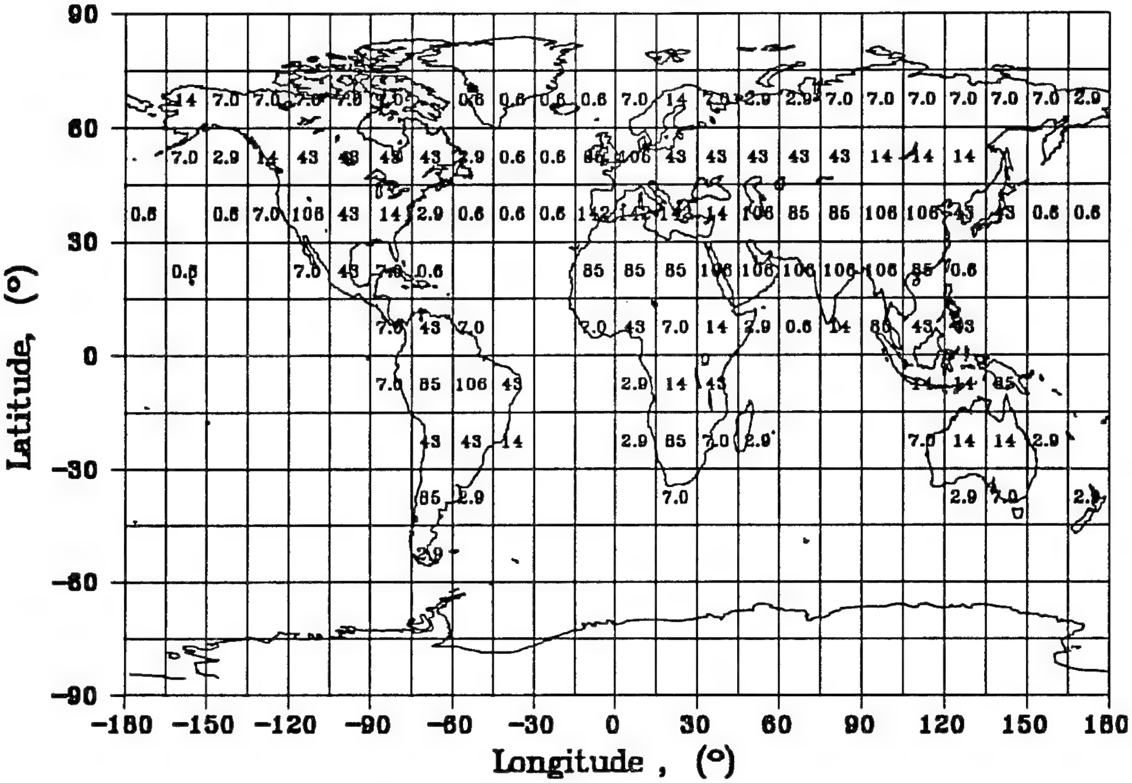
Traffic Growth Model (Year 2001)



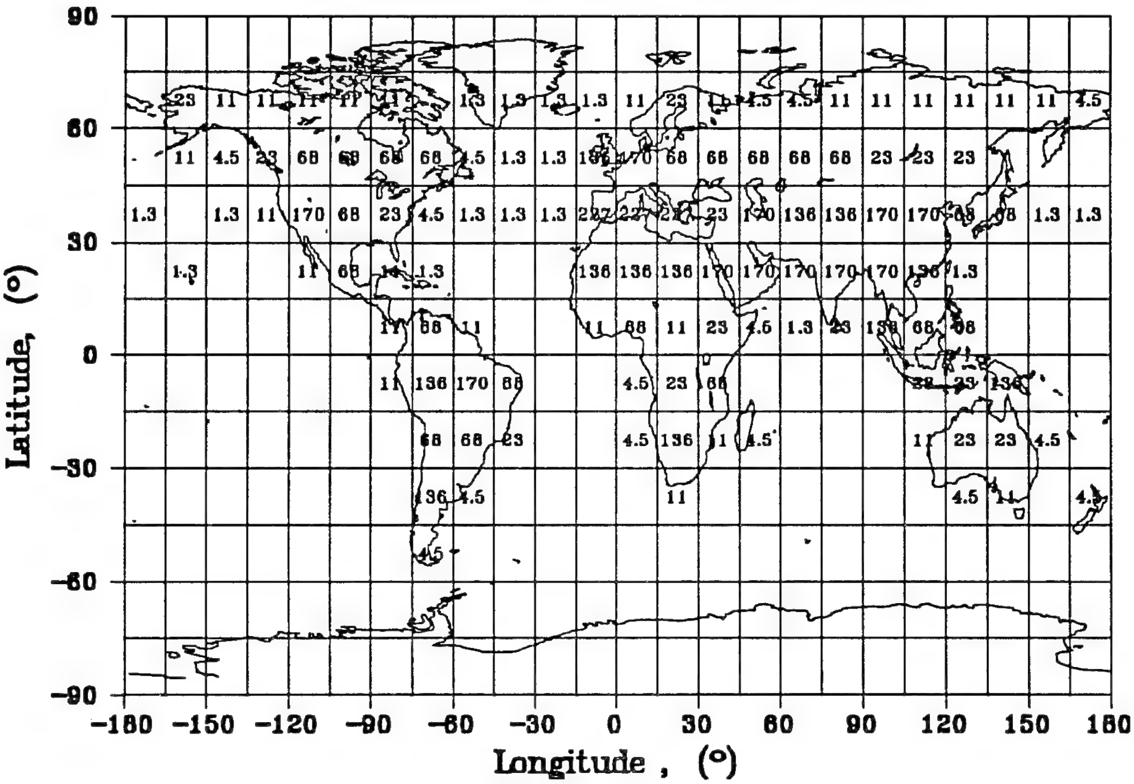
Traffic Growth Model (Year 2002)



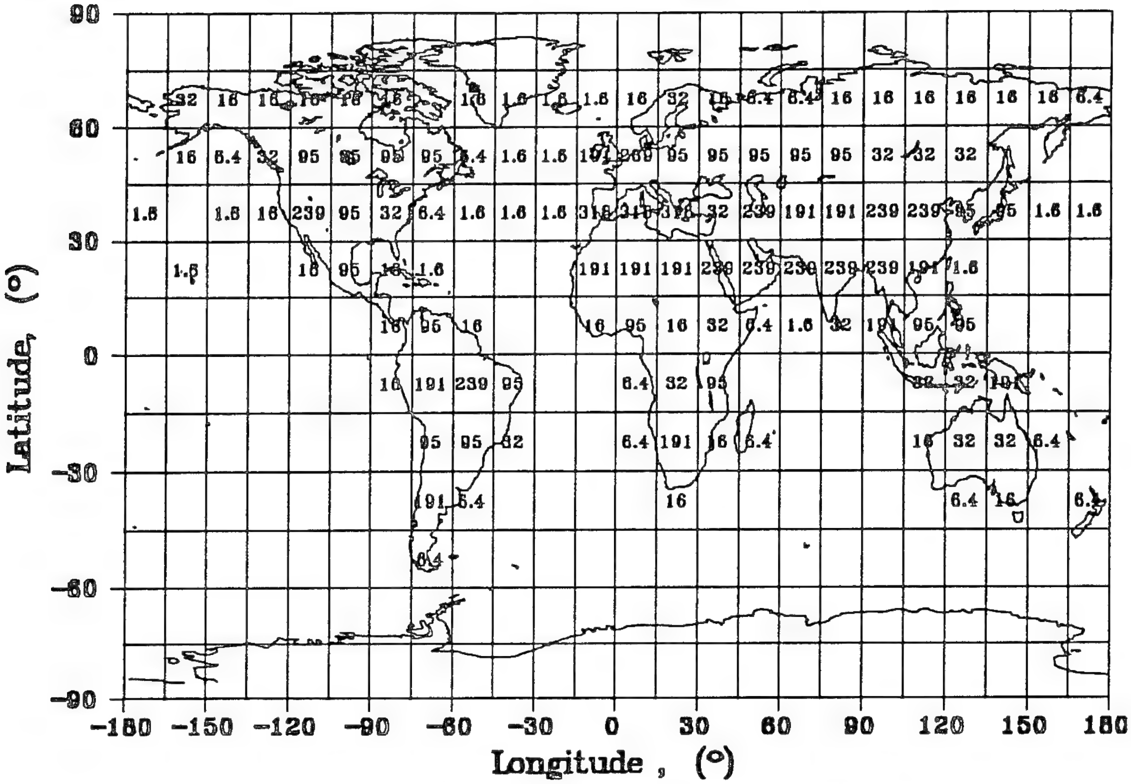
Traffic Growth Model (Year 2003)



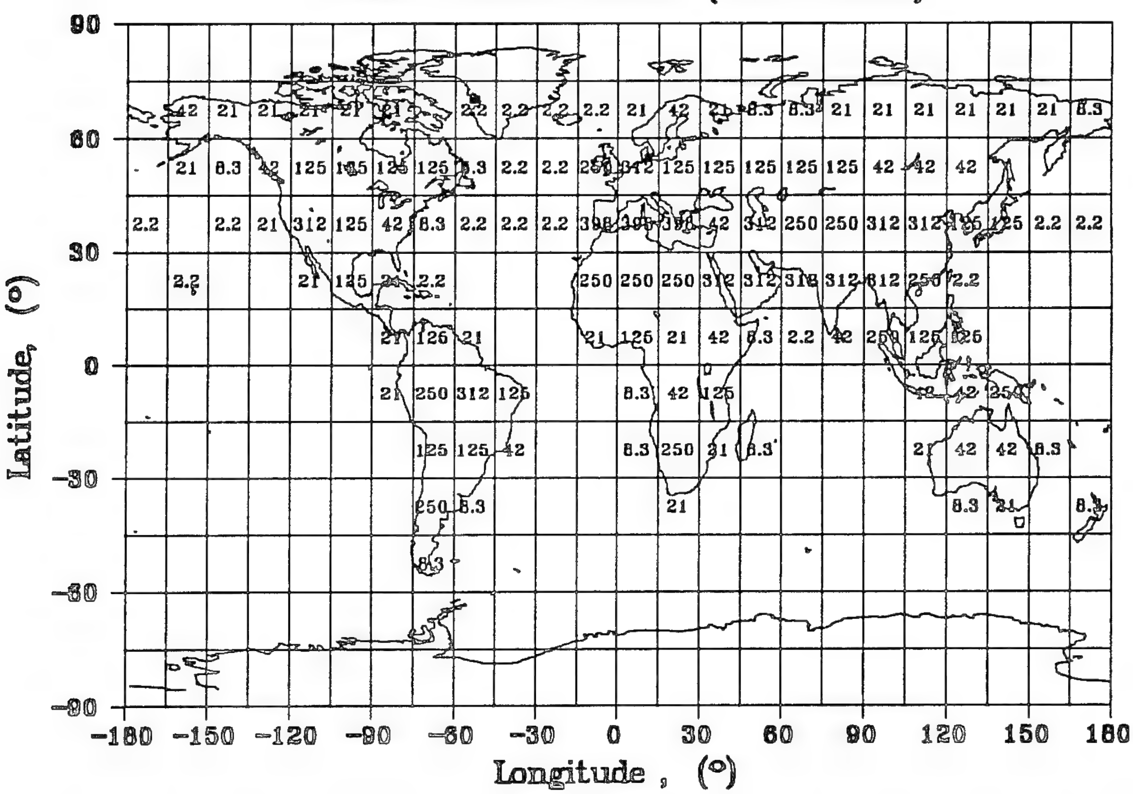
Traffic Growth Model (Year 2004)



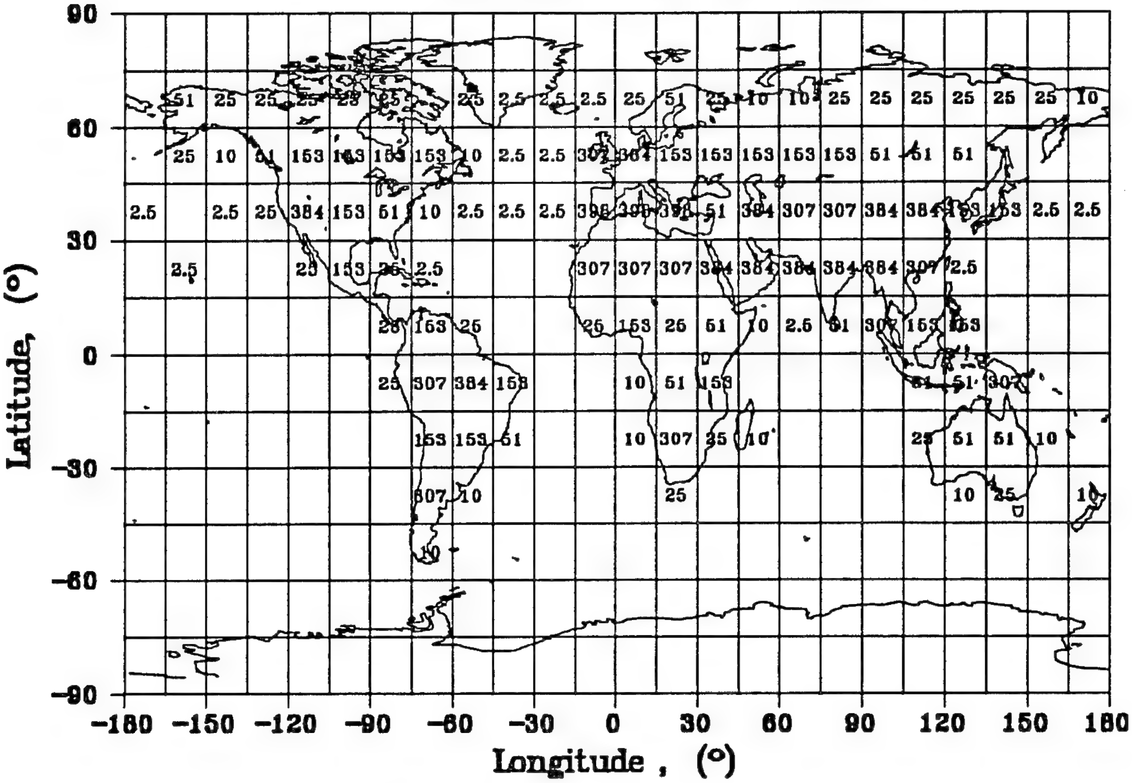
Traffic Growth Model (Year 2005)



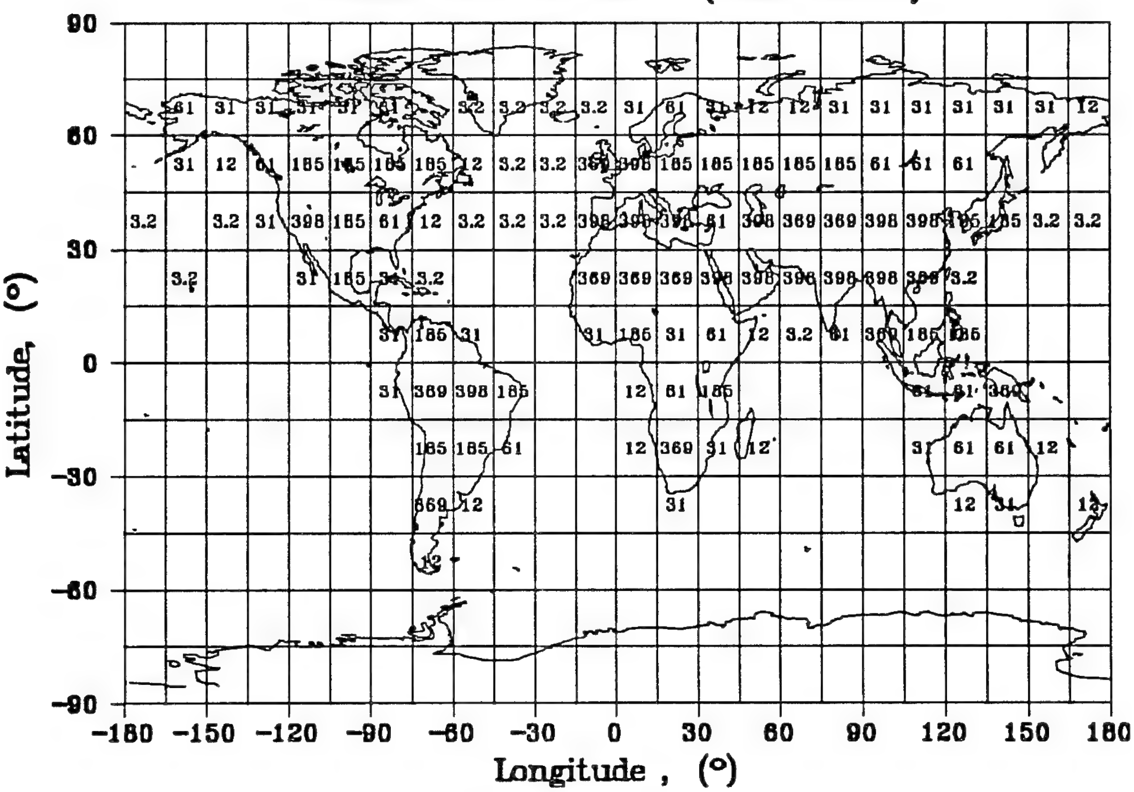
Traffic Growth Model (Year 2006)



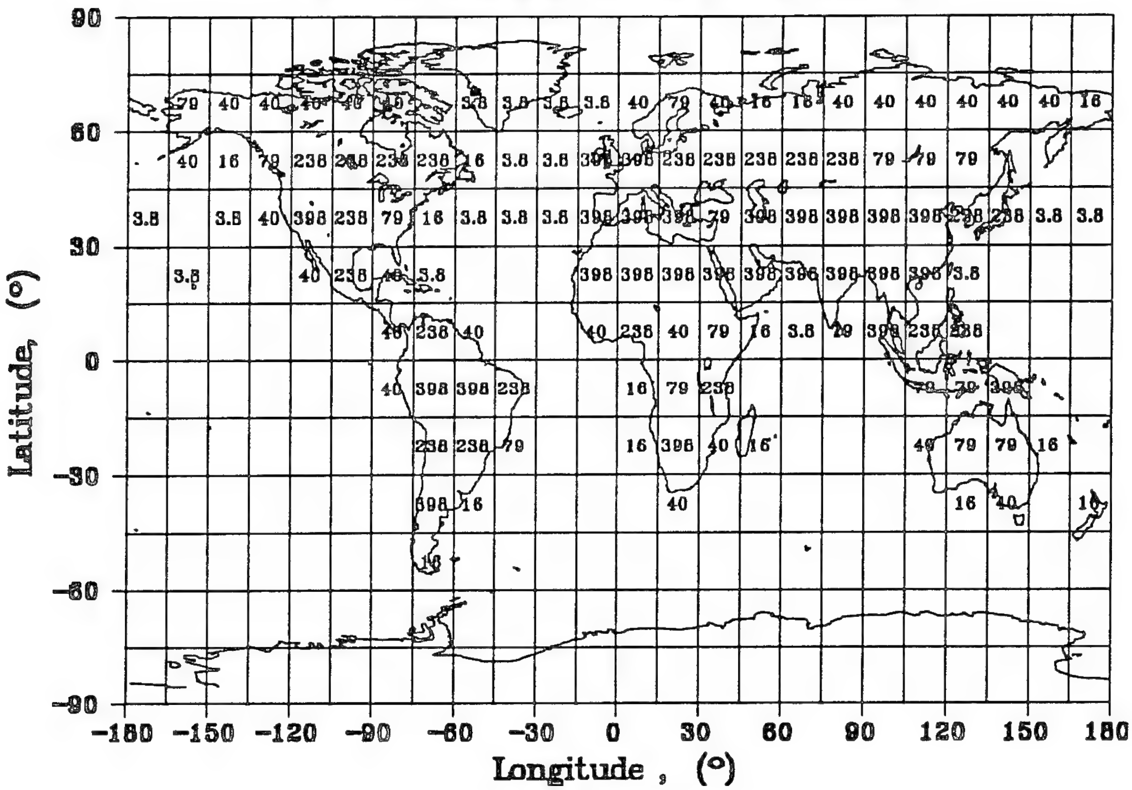
Traffic Growth Model (Year 2007)



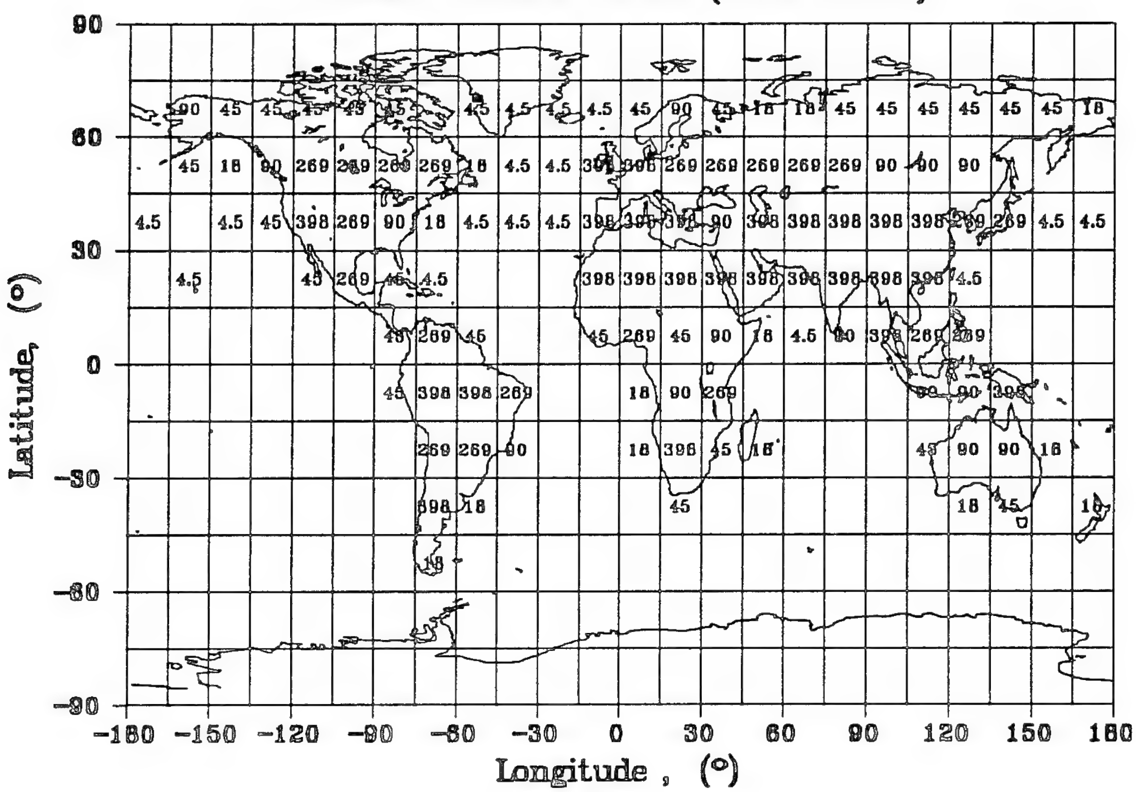
Traffic Growth Model (Year 2008)



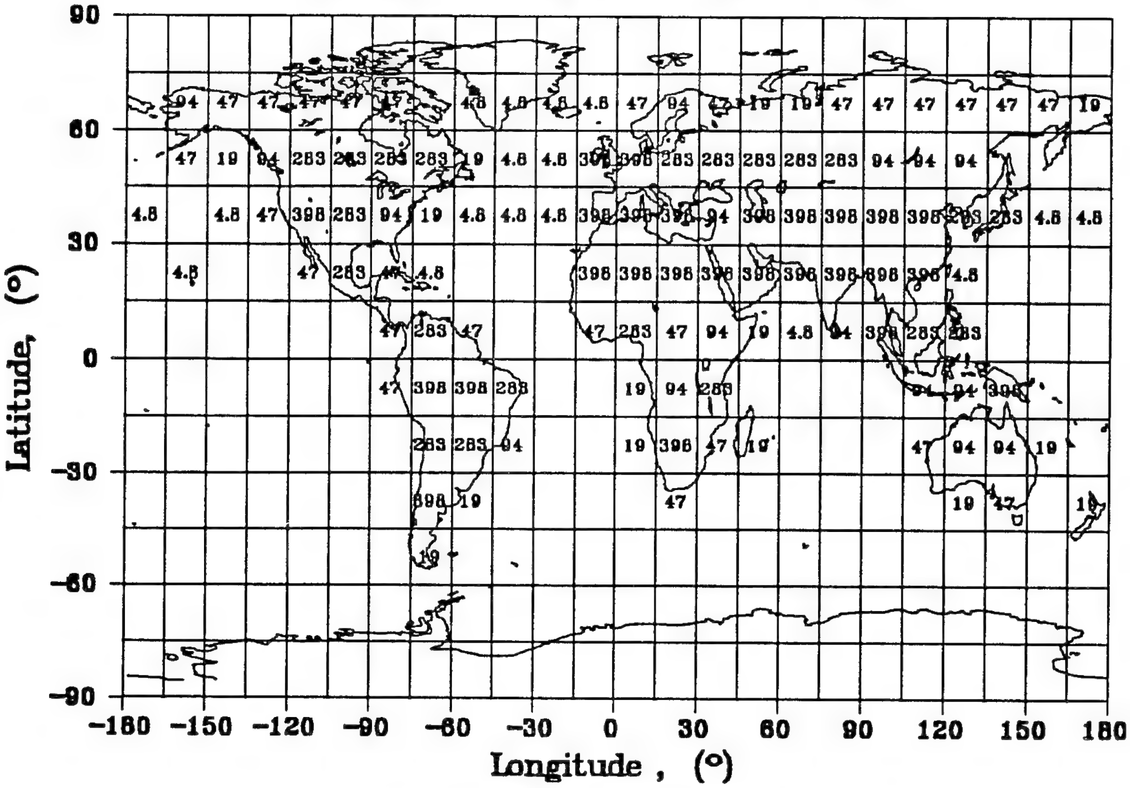
Traffic Growth Model (Year 2009)



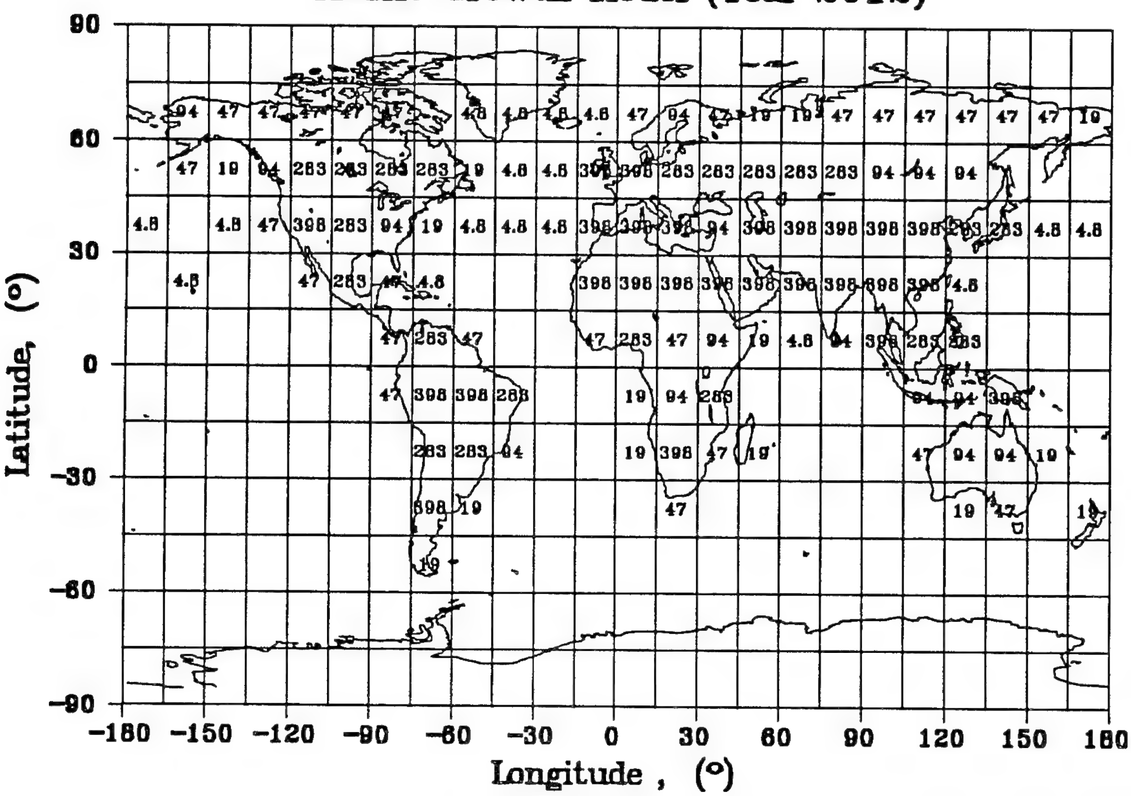
Traffic Growth Model (Year 2010)



Traffic Growth Model (Year 2011)



Traffic Growth Model (Year 2012)



Appendix B: Control Files

This appendix contains the control files used as inputs to the *Vircap* capacity model for each of the modeled systems. The control files include the orbital parameters for each of the satellites in the constellation, the number and location of the gateway antennas, and various aspects of the communications design such as the spotbeam configurations and link budget parameters.

B.1 LEO-66

Orbit Parameters

Satellite	Inclination	Mean Motion	Eccentricity	Ascending Node	Argument Perigee	Mean Anomaly
1	86.4	14.3427357	0.001327625	0.000	90	0
2	86.4	14.3427357	0.001327625	0.000	90	32.7273
3	86.4	14.3427357	0.001327625	0.000	90	65.4545
4	86.4	14.3427357	0.001327625	0.000	90	98.1818
5	86.4	14.3427357	0.001327625	0.000	90	130.9091
6	86.4	14.3427357	0.001327625	0.000	90	163.6364
7	86.4	14.3427357	0.001327625	0.000	90	196.3636
8	86.4	14.3427357	0.001327625	0.000	90	229.0909
9	86.4	14.3427357	0.001327625	0.000	90	261.8182
10	86.4	14.3427357	0.001327625	0.000	90	294.5455
11	86.4	14.3427357	0.001327625	0.000	90	327.2727
12	86.4	14.3427357	0.001327625	31.587	90	15.0636
13	86.4	14.3427357	0.001327625	31.587	90	47.7909
14	86.4	14.3427357	0.001327625	31.587	90	80.5182
15	86.4	14.3427357	0.001327625	31.587	90	113.2455
16	86.4	14.3427357	0.001327625	31.587	90	145.9727
17	86.4	14.3427357	0.001327625	31.587	90	178.6999
18	86.4	14.3427357	0.001327625	31.587	90	211.4273
19	86.4	14.3427357	0.001327625	31.587	90	244.1545
20	86.4	14.3427357	0.001327625	31.587	90	276.8818
21	86.4	14.3427357	0.001327625	31.587	90	309.6091
22	86.4	14.3427357	0.001327625	31.587	90	342.3364
23	86.4	14.3427357	0.001327625	63.174	90	28.8273
24	86.4	14.3427357	0.001327625	63.174	90	61.5546
25	86.4	14.3427357	0.001327625	63.174	90	94.2818
26	86.4	14.3427357	0.001327625	63.174	90	127.0091
27	86.4	14.3427357	0.001327625	63.174	90	159.7364
28	86.4	14.3427357	0.001327625	63.174	90	192.4636
29	86.4	14.3427357	0.001327625	63.174	90	225.1909
30	86.4	14.3427357	0.001327625	63.174	90	257.9182
31	86.4	14.3427357	0.001327625	63.174	90	290.6455
32	86.4	14.3427357	0.001327625	63.174	90	323.3727
33	86.4	14.3427357	0.001327625	63.174	90	356.1000
34	86.4	14.3427357	0.001327625	94.761	90	41.2909
35	86.4	14.3427357	0.001327625	94.761	90	74.0182
36	86.4	14.3427357	0.001327625	94.761	90	106.7455
37	86.4	14.3427357	0.001327625	94.761	90	139.4727
38	86.4	14.3427357	0.001327625	94.761	90	172.2000
39	86.4	14.3427357	0.001327625	94.761	90	204.9273
40	86.4	14.3427357	0.001327625	94.761	90	237.6545
41	86.4	14.3427357	0.001327625	94.761	90	270.3818
42	86.4	14.3427357	0.001327625	94.761	90	303.1091
43	86.4	14.3427357	0.001327625	94.761	90	335.8364
44	86.4	14.3427357	0.001327625	94.761	90	368.5636
45	86.4	14.3427357	0.001327625	126.348	90	52.4546
46	86.4	14.3427357	0.001327625	126.348	90	85.1818
47	86.4	14.3427357	0.001327625	126.348	90	117.9091
48	86.4	14.3427357	0.001327625	126.348	90	150.6364

49	86.4	14.3427357	0.001327625	126.348	90	183.3636
50	86.4	14.3427357	0.001327625	126.348	90	216.0909
51	86.4	14.3427357	0.001327625	126.348	90	248.8182
52	86.4	14.3427357	0.001327625	126.348	90	281.5455
53	86.4	14.3427357	0.001327625	126.348	90	314.2727
54	86.4	14.3427357	0.001327625	126.348	90	347.0000
55	86.4	14.3427357	0.001327625	126.348	90	19.7273
56	86.4	14.3427357	0.001327625	157.94	90	62.3182
57	86.4	14.3427357	0.001327625	157.94	90	95.0454
58	86.4	14.3427357	0.001327625	157.94	90	127.7727
59	86.4	14.3427357	0.001327625	157.94	90	160.5000
60	86.4	14.3427357	0.001327625	157.94	90	193.2273
61	86.4	14.3427357	0.001327625	157.94	90	225.9545
62	86.4	14.3427357	0.001327625	157.94	90	258.6818
63	86.4	14.3427357	0.001327625	157.94	90	291.4091
64	86.4	14.3427357	0.001327625	157.94	90	324.1364
65	86.4	14.3427357	0.001327625	157.94	90	356.8636
66	86.4	14.3427357	0.001327625	157.94	90	29.5909

Gateways

(Intersatellite cross links: gateway in view check disabled.)

Communications

Parameter	Units	Return Uplink	Forward Downlink
Number of spot beams	-	48	48
Number of panels	-	3	3
Number of rings	-	4	4
Access scheme	-	TDD/TDMA	TDD/TDMA
Number of gateway channels	-	3000	3000
Bandwidth channels/beam	-	13	13
Voice circuits/frame	-	4	4
Center frequency	GHz	1.62125	1.62125
Bandwidth	kHz	31.5	31.5
Channel data rate	bps	50000	50000
Voice activity factor	-	1	1
Forward error correction	-	none	none
Average handheld gain	dBi	0	0
Max handheld RF power	W	3.7	n/a
Max beam RF power	W	n/a	123
Max panel RF power	W	n/a	293
Satellite RF Power	W	n/a	128
Required Eb/No (with FEC)	dB	5.8	5.8
Interference Factor α	-	n/a	n/a
Receiver system temperature	K	500	294.6
Circuit losses	dB	-1.5	-1.5
Propagation losses	dB	-1	-1
Power control margin	dB	n/a	2

Ring Data

Parameter	Units	Ring 1	Ring 2	Ring 3	Ring 4
Nadir angle	deg	12.35	31.72	44.69	55.75
Start Azimuth angle	deg	0.0	0.0	0.0	0.0
Number of beams	-	3	9	15	21
Downlink gain	dBi	16.8	22.9	23.1	24.3
Uplink gain	dBi	16.4	22.8	23.1	24.3
Beam width	deg	24.7	15.8	13.6	13.0
PFD limit	$dBW/m^2(4kHz)$	n/a	n/a	n/a	n/a

B.2 LEO-48

Orbit Parameters

Satellite	Inclination	Mean Motion	Eccentricity	Ascending Node	Argument Perigee	Mean Anomaly
1	52	12.631579	0.000758524	0	0	0
2	52	12.631579	0.000758524	0	60	0
3	52	12.631579	0.000758524	0	120	0
4	52	12.631579	0.000758524	0	180	0
5	52	12.631579	0.000758524	0	240	0
6	52	12.631579	0.000758524	0	300	0
7	52	12.631579	0.000758524	45	7.5	0
8	52	12.631579	0.000758524	45	67.5	0
9	52	12.631579	0.000758524	45	127.5	0
10	52	12.631579	0.000758524	45	187.5	0
11	52	12.631579	0.000758524	45	247.5	0
12	52	12.631579	0.000758524	45	307.5	0
13	52	12.631579	0.000758524	90	15	0
14	52	12.631579	0.000758524	90	75	0
15	52	12.631579	0.000758524	90	135	0
16	52	12.631579	0.000758524	90	195	0
17	52	12.631579	0.000758524	90	255	0
18	52	12.631579	0.000758524	90	315	0
19	52	12.631579	0.000758524	135	22.5	0
20	52	12.631579	0.000758524	135	82.5	0
21	52	12.631579	0.000758524	135	142.5	0
22	52	12.631579	0.000758524	135	202.5	0
23	52	12.631579	0.000758524	135	262.5	0
24	52	12.631579	0.000758524	135	322.5	0
25	52	12.631579	0.000758524	180	30	0
26	52	12.631579	0.000758524	180	90	0
27	52	12.631579	0.000758524	180	150	0
28	52	12.631579	0.000758524	180	210	0
29	52	12.631579	0.000758524	180	270	0
30	52	12.631579	0.000758524	180	330	0
31	52	12.631579	0.000758524	225	37.5	0
32	52	12.631579	0.000758524	225	97.5	0
33	52	12.631579	0.000758524	225	157.5	0
34	52	12.631579	0.000758524	225	217.5	0
35	52	12.631579	0.000758524	225	277.5	0
36	52	12.631579	0.000758524	225	337.5	0
37	52	12.631579	0.000758524	270	45	0
38	52	12.631579	0.000758524	270	105	0
39	52	12.631579	0.000758524	270	165	0
40	52	12.631579	0.000758524	270	225	0
41	52	12.631579	0.000758524	270	285	0
42	52	12.631579	0.000758524	270	345	0
43	52	12.631579	0.000758524	315	52.5	0
44	52	12.631579	0.000758524	315	112.5	0
45	52	12.631579	0.000758524	315	172.5	0
46	52	12.631579	0.000758524	315	232.5	0
47	52	12.631579	0.000758524	315	292.5	0
48	52	12.631579	0.000758524	315	352.5	0

Gateways

Site	Latitude	Longitude	Min ε	# Antennas
Adelaide, Australia	-34.92	138.60	10°	4
Atlanta, GA	33.75	-84.38	10°	4
Auckland, New Zealand	-36.87	174.75	10°	4
Belem, Brazil	-1.47	-48.48	10°	4
Bogota, Colombia	4.23	-74.25	10°	4
Calcutta, India	22.57	88.40	10°	4
Calgary, Alberta	51.02	-144.02	10°	4
Cape Town, South Africa	-33.92	18.37	10°	4
Cordoba, Argentina	-31.47	-64.17	10°	4
Dakar, Senegal	14.67	-17.47	10°	4
Hammerfest, Norway	70.63	23.63	10°	4
Helsinki, Finland	60.17	25.00	10°	4
Honolulu, HI	21.30	-157.83	10°	4
Irkutsk, Russia	52.50	104.33	10°	4
Jakarta, Indonesia	-6.27	106.80	10°	4
Kasputin Yar, Russia	48.30	45.90	10°	4
Kinshasa, Zaire	-4.30	15.28	10°	4
Lisbon, Spain	38.75	-9.15	10°	4
Long Beach, CA	33.77	-118.18	10°	4
Mecca, Saudi Arabia	21.48	39.75	10°	4
Nairobi, Kenya	-1.42	36.92	10°	4
Nanjing, China	32.05	118.88	10°	4
Nome, AK	64.42	-165.50	10°	4
Port Maresby, Papua New Guinea	-9.42	147.13	10°	4
St. John, NB	45.30	-66.17	10°	4
Tananarive, Madagascar	-18.83	47.55	10°	4
Tokyo, Japan	35.67	139.75	10°	4
Vladivistok, Russia	50.00	157.00	10°	4

Communications

Parameter	Units	Return Uplink	Forward Downlink
Number of spot beams	-	16	16
Number of panels	-	1	1
Number of rings	-	3	3
Access scheme	-	Channelized CDMA	Channelized CDMA
Number of gateway channels	-	208	208
Bandwidth channels/beam	-	9	13
Voice circuits/frame	-	1	1
Center frequency	GHz	1.62125	2.49500
Bandwidth	MHz	1.23	1.23
Channel data rate	bps	4800	4800
Voice activity factor	-	0.4	0.4
Forward error correction	-	Rate 1/2	Rate 1/2
Average handheld gain	dBi	0	0
Rake handheld gain	dB	0	1.5
Max handheld RF power	W	0.5	0.5
Max beam RF power	W	n/a	60
Max panel RF power	W	n/a	n/a
Satellite RF Power	W	n/a	136
Required Eb/No (with FEC)	dB	4.0	4.0
Interference Factor α	-	1.25	n/a
Receiver system temperature	K	500	293.7
Circuit losses	dB	-1.5	-1.5
Propagation losses	dB	-1	-1
Power control margin	dB	2	2

Ring Data

Parameter	Units	Ring 1	Ring 2	Ring 3
Nadir angle	deg	0.0	25.2	43.51
Start Azimuth angle	deg	0.0	30	10
Number of beams	-	1	6	9
Downlink gain	dBi	11.9	14.8	17.4
Uplink gain	dBi	16.8	18.7	19.4
Beam width	deg	29.4	21.0	15.6
PFD limit	$dBW/m^2(4kHz)$	-142	-142	-142

B.3 MEO-12

Orbit Parameters

Satellite	Inclination	Mean Motion	Eccentricity	Ascending Node	Argument Perigee	Mean Anomaly
1	50	4.010867	0.0000001	0	0	0
2	50	4.010867	0.0000001	0	0	90
3	50	4.010867	0.0000001	0	0	180
4	50	4.010867	0.0000001	0	0	270
5	50	4.010867	0.0000001	240	0	30
6	50	4.010867	0.0000001	240	0	120
7	50	4.010867	0.0000001	240	0	210
8	50	4.010867	0.0000001	240	0	300
9	50	4.010867	0.0000001	120	0	60
10	50	4.010867	0.0000001	120	0	150
11	50	4.010867	0.0000001	120	0	240
12	50	4.010867	0.0000001	120	0	330

Gateways

Site	Latitude	Longitude	Min ε	# Antennas
Auckland, New Zealand	-36.87	174.75	8°	4
Bremen, Germany	13.75	100.50	8°	4
Canton, China	22.58	110.64	8°	4
Cordoba, Argentina	-31.47	-64.17	8°	4
Johannesburg, South Africa	-27.160	32.25	8°	4
Long Beach, California	33.77	-118.18	8°	4

Communications

Parameter	Units	Return Uplink	Forward Downlink
Number of spot beams	-	37	37
Number of panels	-	1	1
Number of rings	-	4	4
Access scheme	-	Channelized CDMA	Channelized CDMA
Number of gateway channels	-	108	108
Bandwidth channels/beam	-	4	6
Voice circuits/frame	-	1	1
Center frequency	GHz	1.615	2.495
Bandwidth	MHz	2.5	2.5
Channel data rate	bps	4620	4620
Voice activity factor	-	0.4	0.4
Forward error correction	-	Rate 1/2	Rate 1/2
Average handheld gain	dBi	0	0
Rake handheld gain	dB	0	0
Max handheld RF power	W	0.5	0.5
Max beam RF power	W	n/a	80
Max panel RF power	W	n/a	n/a
Satellite RF Power	W	n/a	494
Required Eb/No (with FEC)	dB	4.0	4.0
Interference Factor α	-	1.25	n/a
Receiver system temperature	K	409.6	294.6
Circuit losses	dB	-1.5	-1.5
Propagation losses	dB	-1	-1
Power control margin	dB	2	2

Ring Data

Parameter	Units	Ring 1	Ring 2	Ring 3	Ring 4
Nadir angle	deg	0.0	5.66	11.43	17.88
Start Azimuth angle	deg	60	40.5	38.3	32.4
Number of beams	-	1	6	12	18
Downlink gain	dBi	25.0	24.8	23.6	22.5
Uplink gain	dBi	25.0	24.8	23.6	22.5
Beam width	deg	6	6	6	6
PFD limit	$dBW/m^2(4kHz)$	-142	-142	-142	-142

B.4 MITMEO-12

Orbit Parameters

Satellite	Inclination	Mean Motion	Eccentricity	Ascending Node	Argument Perigee	Mean Anomaly
1	45	4.010867	0.0000001	0	0	0
2	45	4.010867	0.0000001	0	0	90
3	45	4.010867	0.0000001	0	0	180
4	45	4.010867	0.0000001	0	0	270
5	45	4.010867	0.0000001	120	0	30
6	45	4.010867	0.0000001	120	0	120
7	45	4.010867	0.0000001	120	0	210
8	45	4.010867	0.0000001	120	0	300
9	45	4.010867	0.0000001	240	0	60
10	45	4.010867	0.0000001	240	0	150
11	45	4.010867	0.0000001	240	0	240
12	45	4.010867	0.0000001	240	0	330

Site	Latitude	Longitude	Min ε	# Antennas
Auckland, New Zealand	-36.87	174.75	8°	4
Bremen, Germany	13.75	100.50	8°	4
Canton, China	22.58	110.64	8°	4
Cordoba, Argentina	-31.47	-64.17	8°	4
Johannesburg, South Africa	-27.160	32.25	8°	4
Long Beach, California	33.77	-118.18	8°	4

Communications

Parameter	Units	Return Uplink	Forward Downlink
Number of spot beams	-	48	48
Number of panels	-	4	4
Number of rings	-	4	4
Access scheme	-	Channelized CDMA	Channelized CDMA
Number of gateway channels	-	1620	1620
Bandwidth channels/beam	-	8	12
Voice circuits/frame	-	1	1
Center frequency	GHz	1.615	2.495
Bandwidth	MHz	1.23	1.23
Channel data rate	bps	4800	4800
Voice activity factor	-	0.4	0.4
Forward error correction	-	Rate 1/2	Rate 1/2
Average handheld gain	dBi	0	0
Rake handheld gain	dB	0	0
Max handheld RF power	W	0.5	0.5
Max beam RF power	W	n/a	80
Max panel RF power	W	n/a	125
Satellite RF Power	W	n/a	475
Required Eb/No (with FEC)	dB	4.0	4.0
Interference Factor α	-	1.25	n/a
Receiver system temperature	K	400	294.6
Circuit losses	dB	-1.5	-1.5
Propagation losses	dB	-1	-1
Power control margin	dB	2	2

Ring Data

Parameter	Units	Ring 1	Ring 2	Ring 3	Ring 4
Nadir angle	deg	2.29	7.05	12.20	19.95
Start Azimuth angle	deg	0	0	0	0
Number of beams	-	4	10	15	19
Downlink gain	dBi	27.3	26.7	25.9	24.8
Uplink gain	dBi	27.3	26.7	25.9	24.8
Beam width	deg	4.49	4.92	5.34	6.10
PFD limit	$dBW/m^2(4kHz)$	-142	-142	-142	-142

B.5 GEO-3

Orbit Parameters

Satellite	Inclination	Mean Motion	Eccentricity	Ascending Node	Argument Perigee	Mean Anomaly
1	0	1.0	0.000000001	0	358.8645	0
2	0	1.0	0.000000001	0	118.7572	0
3	0	1.0	0.000000001	0	236.6496	0

Site	Latitude	Longitude	Min ε	# Antennas
Darwin Autralia	8.97	-79.53	5°	2
Nairobi, Kenya	-1.42	36.92	5°	2
Panama City, Panama	-12.47	130.85	5°	2

Communications

Parameter	Units	Return Uplink	Forward Downlink
Access scheme	-	Channelized CDMA	Channelized CDMA
Number of gateway channels	-	185	185
Bandwidth channels/beam	-	1	1
Voice circuits/frame	-	1	1
Center frequency	GHz	1.615	1.55
Bandwidth	MHz	14	14
Channel data rate	bps	4800	4800
Voice activity factor	-	0.4	0.4
Forward error correction	-	Rate 1/2	Rate 1/2
Average handheld gain	dBi	0	0
Rake handheld gain	dB	0	0
Max handheld RF power	W	0.5	0.5
Max beam RF power	W	n/a	10
Max panel RF power	W	n/a	n/a
Satellite RF Power	W	n/a	1093
Required Eb/No (with FEC)	dB	4.0	4.0
Interference Factor α	-	1.25	n/a
Receiver system temperature	K	400	294.6
Circuit losses	dB	-1.5	-1.5
Propagation losses	dB	-1	-1
Power control margin	dB	2	2

Beam Data, Satellite 1

Beam number	Nadir angle[deg]	Azimuth angle [deg]	Downlink gain [dB]	Uplink gain [dB]	Beam width [deg]	PFD dBW/m²(4kHz)
1	7.9	-82.7	31.0	31.0	3	-142
2	-8.0	-75.6	40.5	40.5	1	-142
3	-8.4	-68.9	40.5	40.5	1	-142
4	-6.9	-85.9	40.5	40.5	1	-142
5	-7.1	-77.8	40.5	40.5	1	-142
6	-7.4	-70.1	40.5	40.5	1	-142
7	-7.8	-63.1	40.5	40.5	1	-142
8	-8.3	-56.9	40.5	40.5	1	-142
9	6.1	90.0	40.5	40.5	1	-142
10	-6.1	-80.6	40.5	40.5	1	-142
11	-6.4	-71.7	40.5	40.5	1	-142
12	6.8	-63.6	31.0	31.0	3	-142
13	-6.8	-63.6	40.5	40.5	1	-142
14	-7.3	-56.5	40.5	40.5	1	-142
15	-7.9	-50.4	40.5	40.5	1	-142
16	8.6	-45.2	40.5	40.5	1	-142
17	-8.6	-45.2	40.5	40.5	1	-142
18	5.2	-84.5	31.0	31.0	3	-142
19	-5.2	-84.5	40.5	40.5	1	-142
20	-5.4	-73.9	40.5	40.5	1	-142
21	-5.8	-64.3	40.5	40.5	1	-142
22	-6.3	-56.0	40.5	40.5	1	-142
23	-6.9	-49.1	40.5	40.5	1	-142
24	-7.6	-43.3	40.5	40.5	1	-142
25	-8.3	-38.6	40.5	40.5	1	-142
26	4.3	90.0	40.5	40.5	1	-142
27	-4.4	-77.0	40.5	40.5	1	-142
28	-4.8	-65.2	40.5	40.5	1	-142
29	-5.3	-55.3	40.5	40.5	1	-142
30	-5.9	-47.2	40.5	40.5	1	-142
31	6.6	-40.9	31.0	31.0	3	-142
32	-6.6	-40.9	40.5	40.5	1	-142
33	-7.4	-35.8	40.5	40.5	1	-142
34	8.3	-31.7	40.5	40.5	1	-142
35	-8.3	-31.7	40.5	40.5	1	-142
36	4.3	-54.2	31.0	31.0	3	-142
37	-4.3	-54.2	40.5	40.5	1	-142
38	-4.9	-44.7	40.5	40.5	1	-142
39	-5.7	-37.6	40.5	40.5	1	-142
40	-6.5	-32.2	40.5	40.5	1	-142
41	7.4	-28.0	40.5	40.5	1	-142
42	-7.4	-28.0	40.5	40.5	1	-142
43	8.3	-24.8	40.5	40.5	1	-142
44	-8.3	-24.8	40.5	40.5	1	-142
45	-2.8	-68.9	31.0	31.0	3	-142
46	-4.0	-40.9	40.5	40.5	1	-142
47	4.8	-33.0	40.5	40.5	1	-142
48	-4.8	-33.0	40.5	40.5	1	-142
49	5.6	-27.4	40.5	40.5	1	-142
50	6.6	-23.4	40.5	40.5	1	-142
51	7.5	-20.4	40.5	40.5	1	-142

52	-7.5	-20.4	40.5	40.5	1	-142
53	8.4	-18.0	40.5	40.5	1	-142
54	-8.4	-18.0	40.5	40.5	1	-142
55	3.9	-26.3	40.5	40.5	1	-142
56	4.8	-21.0	40.5	40.5	1	-142
57	5.8	-17.5	40.5	40.5	1	-142
58	-5.8	-17.5	31.0	31.0	3	-142
59	6.7	-14.9	40.5	40.5	1	-142
60	7.7	-13.0	40.5	40.5	1	-142
61	-7.7	-13.0	40.5	40.5	1	-142
62	2.2	-23.4	31.0	31.0	3	-142
63	-3.1	-16.1	31.0	31.0	3	-142
64	4.1	-12.2	40.5	40.5	1	-142
65	5.1	-9.8	40.5	40.5	1	-142
66	6.1	-8.2	40.5	40.5	1	-142
67	7.1	-7.1	40.5	40.5	1	-142
68	8.1	-6.2	40.5	40.5	1	-142
69	-0.5	0.0	31.0	31.0	3	-142
70	3.5	0.0	40.5	40.5	1	-142
71	4.5	0.0	40.5	40.5	1	-142
72	5.5	0.0	40.5	40.5	1	-142
73	6.5	0.0	40.5	40.5	1	-142
74	7.5	0.0	40.5	40.5	1	-142
75	-7.5	0.0	31.0	31.0	3	-142
76	8.5	0.0	40.5	40.5	1	-142
77	3.1	16.1	40.5	40.5	1	-142
78	4.1	12.2	40.5	40.5	1	-142
79	5.1	9.8	40.5	40.5	1	-142
80	-5.1	9.8	31.0	31.0	3	-142
81	6.1	8.2	40.5	40.5	1	-142
82	7.1	7.1	40.5	40.5	1	-142
83	8.1	6.2	40.5	40.5	1	-142
84	2.3	49.1	31.0	31.0	3	-142
85	-3.0	34.7	31.0	31.0	3	-142
86	3.9	26.3	40.5	40.5	1	-142
87	4.8	21.0	40.5	40.5	1	-142
88	5.8	17.5	40.5	40.5	1	-142
89	6.7	14.9	40.5	40.5	1	-142
90	7.7	13.0	40.5	40.5	1	-142
91	-2.6	90.0	31.0	31.0	3	-142
92	4.0	40.9	40.5	40.5	1	-142
93	4.8	33.0	40.5	40.5	1	-142
94	5.6	27.4	40.5	40.5	1	-142
95	6.6	23.4	40.5	40.5	1	-142
96	7.5	20.4	40.5	40.5	1	-142
97	-7.5	20.4	31.0	31.0	3	-142
98	8.4	18.0	40.5	40.5	1	-142
99	3.5	81.8	40.5	40.5	1	-142
100	3.8	66.6	40.5	40.5	1	-142
101	4.3	54.2	40.5	40.5	1	-142
102	4.9	44.7	40.5	40.5	1	-142
103	5.7	37.6	40.5	40.5	1	-142
104	-5.7	37.6	31.0	31.0	3	-142
105	6.5	32.2	40.5	40.5	1	-142
106	7.4	28.0	40.5	40.5	1	-142

107	8.3	24.8	40.5	40.5	1	-142
108	4.4	77.0	40.5	40.5	1	-142
109	4.8	65.2	40.5	40.5	1	-142
110	-4.8	65.2	31.0	31.0	3	-142
111	5.3	55.3	40.5	40.5	1	-142
112	5.9	47.2	40.5	40.5	1	-142
113	8.3	31.7	40.5	40.5	1	-142
114	5.2	84.5	40.5	40.5	1	-142
115	5.4	73.9	40.5	40.5	1	-142
116	5.8	64.3	40.5	40.5	1	-142
117	6.3	56.0	40.5	40.5	1	-142
118	7.6	43.3	31.0	31.0	3	-142
119	-8.3	38.6	31.0	31.0	3	-142
120	6.1	80.6	40.5	40.5	1	-142
121	6.4	71.7	40.5	40.5	1	-142
122	-7.3	56.5	31.0	31.0	3	-142
123	6.9	85.9	40.5	40.5	1	-142
124	7.1	77.8	40.5	40.5	1	-142
125	-7.1	77.8	31.0	31.0	3	-142
126	7.8	63.1	31.0	31.0	3	-142
127	7.8	90.0	40.5	40.5	1	-142
128	7.9	82.7	40.5	40.5	1	-142
129	-7.9	-82.7	40.5	40.5	1	-142
130	-8.8	-62.8	40.5	40.5	1	-142
131	-8.3	-56.9	40.5	40.5	1	-142
132	8.7	-11.5	40.5	40.5	1	-142
133	-8.7	-11.5	40.5	40.5	1	-142
134	8.7	11.5	40.5	40.5	1	-142

Beam Data, Satellite 2

Beam number	Nadir angle [deg]	Azimuth angle [deg]	Downlink gain [dB]	Uplink gain [dB]	Beam width [deg]	PFD $dBW/m^2(4kHz)$
1	-7.9	-82.7	40.5	40.5	1	-142
2	-8.0	-75.6	40.5	40.5	1	-142
3	-7.1	-77.8	40.5	40.5	1	-142
4	7.4	-70.1	31.0	31.0	3	-142
5	6.1	90.0	31.0	31.0	3	-142
6	-6.8	-63.6	31.0	31.0	3	-142
7	7.9	-50.4	31.0	31.0	3	-142
8	-7.9	-50.4	40.5	40.5	1	-142
9	5.4	-73.9	40.5	40.5	1	-142
10	-5.4	-73.9	40.5	40.5	1	-142
11	5.8	-64.3	40.5	40.5	1	-142
12	6.3	-56.0	40.5	40.5	1	-142
13	8.3	-38.6	40.5	40.5	1	-142
14	4.3	90.0	40.5	40.5	1	-142
15	4.4	-77.0	40.5	40.5	1	-142
16	-4.4	-77.0	40.5	40.5	1	-142
17	4.8	-65.2	40.5	40.5	1	-142
18	-4.8	-65.2	40.5	40.5	1	-142
19	5.3	-55.3	40.5	40.5	1	-142
20	-5.3	-55.3	40.5	40.5	1	-142
21	5.9	-47.2	40.5	40.5	1	-142
22	6.6	-40.9	40.5	40.5	1	-142
23	-6.6	-40.9	31.0	31.0	3	-142
24	7.4	-35.8	40.5	40.5	1	-142
25	8.3	-31.7	40.5	40.5	1	-142
26	-8.3	-31.7	40.5	40.5	1	-142
27	-3.5	-81.8	40.5	40.5	1	-142
28	3.8	-66.6	40.5	40.5	1	-142
29	-3.8	-66.6	40.5	40.5	1	-142
30	4.3	-54.2	40.5	40.5	1	-142
31	-4.3	-54.2	40.5	40.5	1	-142
32	4.9	-44.7	40.5	40.5	1	-142
33	-4.9	-44.7	40.5	40.5	1	-142
34	5.7	-37.6	40.5	40.5	1	-142
35	6.5	-32.2	40.5	40.5	1	-142
36	7.4	-28.0	40.5	40.5	1	-142
37	8.3	-24.8	40.5	40.5	1	-142
38	2.8	-68.9	40.5	40.5	1	-142
39	-2.8	-68.9	40.5	40.5	1	-142
40	3.3	-52.4	40.5	40.5	1	-142
41	-3.3	-52.4	40.5	40.5	1	-142
42	4.0	-40.9	40.5	40.5	1	-142
43	-4.0	-40.9	40.5	40.5	1	-142
44	4.8	-33.0	40.5	40.5	1	-142
45	-4.8	-33.0	40.5	40.5	1	-142
46	5.6	-27.4	40.5	40.5	1	-142
47	-5.6	-27.4	40.5	40.5	1	-142
48	6.6	-23.4	40.5	40.5	1	-142
49	7.5	-20.4	40.5	40.5	1	-142
50	-7.5	-20.4	31.0	31.0	3	-142
51	8.4	-18.0	40.5	40.5	1	-142

52	1.8	-73.9	40.5	40.5	1	-142
53	-1.8	-73.9	40.5	40.5	1	-142
54	2.3	-49.1	40.5	40.5	1	-142
55	-2.3	-49.1	40.5	40.5	1	-142
56	3.0	-34.7	40.5	40.5	1	-142
57	-3.0	-34.7	40.5	40.5	1	-142
58	3.9	-26.3	40.5	40.5	1	-142
59	-3.9	-26.3	40.5	40.5	1	-142
60	4.8	-21.0	40.5	40.5	1	-142
61	-4.8	-21.0	40.5	40.5	1	-142
62	5.8	-17.5	40.5	40.5	1	-142
63	-5.8	-17.5	40.5	40.5	1	-142
64	6.7	-14.9	40.5	40.5	1	-142
65	7.7	-13.0	40.5	40.5	1	-142
66	-0.9	90.0	40.5	40.5	1	-142
67	0.9	90.0	40.5	40.5	1	-142
68	1.3	-40.9	40.5	40.5	1	-142
69	-1.3	-40.9	40.5	40.5	1	-142
70	2.2	-23.4	40.5	40.5	1	-142
71	-2.2	-23.4	40.5	40.5	1	-142
72	3.1	-16.1	40.5	40.5	1	-142
73	-3.1	-16.1	40.5	40.5	1	-142
74	4.1	-12.2	40.5	40.5	1	-142
75	-4.1	-12.2	40.5	40.5	1	-142
76	5.1	-9.8	40.5	40.5	1	-142
77	-5.1	-9.8	40.5	40.5	1	-142
78	6.1	-8.2	40.5	40.5	1	-142
79	-6.1	-8.2	40.5	40.5	1	-142
80	7.1	-7.1	40.5	40.5	1	-142
81	8.1	-6.2	40.5	40.5	1	-142
82	0.5	0.0	40.5	40.5	1	-142
83	-0.5	0.0	40.5	40.5	1	-142
84	1.5	0.0	40.5	40.5	1	-142
85	-1.5	0.0	40.5	40.5	1	-142
86	2.5	0.0	40.5	40.5	1	-142
87	-2.5	0.0	40.5	40.5	1	-142
88	3.5	0.0	40.5	40.5	1	-142
89	-3.5	0.0	40.5	40.5	1	-142
90	4.5	0.0	40.5	40.5	1	-142
91	-4.5	0.0	40.5	40.5	1	-142
92	5.5	0.0	40.5	40.5	1	-142
93	-5.5	0.0	40.5	40.5	1	-142
94	6.5	0.0	40.5	40.5	1	-142
95	7.5	0.0	40.5	40.5	1	-142
96	-7.5	0.0	31.0	31.0	3	-142
97	1.3	40.9	40.5	40.5	1	-142
98	-1.3	40.9	40.5	40.5	1	-142
99	2.2	23.4	40.5	40.5	1	-142
100	-2.2	23.4	40.5	40.5	1	-142
101	3.1	16.1	40.5	40.5	1	-142
102	-3.1	16.1	40.5	40.5	1	-142
103	4.1	12.2	40.5	40.5	1	-142
104	-4.1	12.2	40.5	40.5	1	-142
105	5.1	9.8	40.5	40.5	1	-142
106	6.1	8.2	40.5	40.5	1	-142

107	7.1	7.1	40.5	40.5	1	-142
108	8.1	6.2	40.5	40.5	1	-142
109	1.8	73.9	40.5	40.5	1	-142
110	-1.8	73.9	40.5	40.5	1	-142
111	2.3	49.1	40.5	40.5	1	-142
112	-2.3	49.1	40.5	40.5	1	-142
113	3.0	34.7	40.5	40.5	1	-142
114	3.9	26.3	40.5	40.5	1	-142
115	4.8	21.0	40.5	40.5	1	-142
116	5.8	17.5	40.5	40.5	1	-142
117	-5.8	17.5	31.0	31.0	3	-142
118	6.7	14.9	40.5	40.5	1	-142
119	7.7	13.0	40.5	40.5	1	-142
120	2.6	90.0	40.5	40.5	1	-142
121	2.8	68.9	40.5	40.5	1	-142
122	3.3	52.4	40.5	40.5	1	-142
123	4.0	40.9	40.5	40.5	1	-142
124	-4.0	40.9	31.0	31.0	3	-142
125	4.8	33.0	40.5	40.5	1	-142
126	5.6	27.4	40.5	40.5	1	-142
127	6.6	23.4	40.5	40.5	1	-142
128	7.5	20.4	40.5	40.5	1	-142
129	8.4	18.0	40.5	40.5	1	-142
130	-8.4	18.0	31.0	31.0	3	-142
131	3.5	81.8	40.5	40.5	1	-142
132	-3.5	81.8	31.0	31.0	3	-142
133	3.8	66.6	40.5	40.5	1	-142
134	4.3	54.2	40.5	40.5	1	-142
135	4.9	44.7	40.5	40.5	1	-142
136	5.7	37.6	40.5	40.5	1	-142
137	6.5	32.2	40.5	40.5	1	-142
138	7.4	28.0	40.5	40.5	1	-142
139	-7.4	28.0	40.5	40.5	1	-142
140	8.3	24.8	40.5	40.5	1	-142
141	4.4	77.0	40.5	40.5	1	-142
142	4.8	65.2	40.5	40.5	1	-142
143	5.3	55.3	40.5	40.5	1	-142
144	5.9	47.2	40.5	40.5	1	-142
145	6.6	40.9	40.5	40.5	1	-142
146	-6.6	40.9	31.0	31.0	3	-142
147	7.4	35.8	40.5	40.5	1	-142
148	8.3	31.7	40.5	40.5	1	-142
149	-8.3	31.7	40.5	40.5	1	-142
150	5.4	73.9	40.5	40.5	1	-142
151	5.8	64.3	40.5	40.5	1	-142
152	-5.8	64.3	31.0	31.0	3	-142
153	6.3	56.0	40.5	40.5	1	-142
154	6.9	49.1	40.5	40.5	1	-142
155	7.6	43.3	40.5	40.5	1	-142
156	8.3	38.6	40.5	40.5	1	-142
157	-6.1	90.0	31.0	31.0	3	-142
158	6.4	71.7	40.5	40.5	1	-142
159	6.8	63.6	40.5	40.5	1	-142
160	7.3	56.5	40.5	40.5	1	-142
161	-7.3	56.5	40.5	40.5	1	-142

162	7.9	50.4	40.5	40.5	1	-142
163	8.6	45.2	40.5	40.5	1	-142
164	7.1	77.8	40.5	40.5	1	-142
165	-7.1	77.8	40.5	40.5	1	-142
166	7.4	70.1	40.5	40.5	1	-142
167	-7.4	70.1	40.5	40.5	1	-142
168	7.8	63.1	40.5	40.5	1	-142
169	8.3	56.9	40.5	40.5	1	-142
170	7.8	90.0	40.5	40.5	1	-142
171	7.9	82.7	40.5	40.5	1	-142
172	8.0	75.6	40.5	40.5	1	-142
173	8.7	-11.5	40.5	40.5	1	-142
174	8.5	0.0	40.5	40.5	1	-142
175	7.7	13.0	40.5	40.5	1	-142

Beam Data, Satellite 3

Beam number	Nadir angle [deg]	Azimuth angle [deg]	Downlink gain [dB]	Uplink gain [dB]	Beam width [deg]	PFD dBW/m²(4kHz)
1	7.9	-82.7	40.5	40.5	1	-142
2	-7.9	-82.7	40.5	40.5	1	-142
3	8.0	-75.6	40.5	40.5	1	-142
4	8.4	-68.9	40.5	40.5	1	-142
5	6.9	-85.9	40.5	40.5	1	-142
6	-6.9	-85.9	40.5	40.5	1	-142
7	7.1	-77.8	40.5	40.5	1	-142
8	7.4	-70.1	40.5	40.5	1	-142
9	7.8	-63.1	40.5	40.5	1	-142
10	-7.8	-63.1	40.5	40.5	1	-142
11	-6.1	90.0	40.5	40.5	1	-142
12	6.1	-80.6	40.5	40.5	1	-142
13	6.4	-71.7	40.5	40.5	1	-142
14	-6.4	-71.7	31.0	31.0	3	-142
15	6.8	-63.6	40.5	40.5	1	-142
16	7.3	-56.5	40.5	40.5	1	-142
17	7.9	-50.4	40.5	40.5	1	-142
18	-7.9	-50.4	40.5	40.5	1	-142
19	5.2	-84.5	40.5	40.5	1	-142
20	5.4	-73.9	40.5	40.5	1	-142
21	5.8	-64.3	40.5	40.5	1	-142
22	6.3	-56.0	40.5	40.5	1	-142
23	6.9	-49.1	40.5	40.5	1	-142
24	7.6	-43.3	40.5	40.5	1	-142
25	-8.3	-38.6	40.5	40.5	1	-142
26	-4.3	90.0	40.5	40.5	1	-142
27	4.4	-77.0	40.5	40.5	1	-142
28	-4.4	-77.0	31.0	31.0	3	-142
29	4.8	-65.2	40.5	40.5	1	-142
30	5.3	-55.3	40.5	40.5	1	-142
31	5.9	-47.2	40.5	40.5	1	-142
32	-5.9	-47.2	31.0	31.0	3	-142
33	6.6	-40.9	40.5	40.5	1	-142
34	7.4	-35.8	40.5	40.5	1	-142
35	-7.4	-35.8	40.5	40.5	1	-142
36	8.3	-31.7	40.5	40.5	1	-142
37	-8.3	-31.7	40.5	40.5	1	-142
38	3.5	-81.8	40.5	40.5	1	-142
39	3.8	-66.6	40.5	40.5	1	-142
40	4.3	-54.2	40.5	40.5	1	-142
41	-4.3	-54.2	40.5	40.5	1	-142
42	4.9	-44.7	40.5	40.5	1	-142
43	5.7	-37.6	40.5	40.5	1	-142
44	6.5	-32.2	40.5	40.5	1	-142
45	-6.5	-32.2	40.5	40.5	1	-142
46	7.4	-28.0	40.5	40.5	1	-142
47	-7.4	-28.0	40.5	40.5	1	-142
48	8.3	-24.8	40.5	40.5	1	-142
49	-8.3	-24.8	40.5	40.5	1	-142
50	-2.6	90.0	40.5	40.5	1	-142
51	2.6	90.0	40.5	40.5	1	-142

52	2.8	-68.9	40.5	40.5	1	-142
53	-2.8	-68.9	40.5	40.5	1	-142
54	3.3	-52.4	40.5	40.5	1	-142
55	-3.3	-52.4	40.5	40.5	1	-142
56	4.0	-40.9	40.5	40.5	1	-142
57	-4.0	-40.9	40.5	40.5	1	-142
58	4.8	-33.0	40.5	40.5	1	-142
59	-4.8	-33.0	40.5	40.5	1	-142
60	5.6	-27.4	40.5	40.5	1	-142
61	-5.6	-27.4	40.5	40.5	1	-142
62	6.6	-23.4	40.5	40.5	1	-142
63	-6.6	-23.4	40.5	40.5	1	-142
64	7.5	-20.4	40.5	40.5	1	-142
65	-7.5	-20.4	40.5	40.5	1	-142
66	8.4	-18.0	40.5	40.5	1	-142
67	-8.4	-18.0	40.5	40.5	1	-142
68	1.8	-73.9	40.5	40.5	1	-142
69	-1.8	-73.9	40.5	40.5	1	-142
70	2.3	-49.1	40.5	40.5	1	-142
71	-2.3	-49.1	40.5	40.5	1	-142
72	-3.0	-34.7	40.5	40.5	1	-142
73	-3.9	-26.3	40.5	40.5	1	-142
74	4.8	-21.0	40.5	40.5	1	-142
75	-4.8	-21.0	40.5	40.5	1	-142
76	5.8	-17.5	40.5	40.5	1	-142
77	-5.8	-17.5	40.5	40.5	1	-142
78	6.7	-14.9	40.5	40.5	1	-142
79	-6.7	-14.9	40.5	40.5	1	-142
80	7.7	-13.0	40.5	40.5	1	-142
81	-7.7	-13.0	40.5	40.5	1	-142
82	-0.9	90.0	40.5	40.5	1	-142
83	1.3	-40.9	40.5	40.5	1	-142
84	-1.3	-40.9	40.5	40.5	1	-142
85	-2.2	-23.4	40.5	40.5	1	-142
86	3.1	-16.1	31.0	31.0	3	-142
87	-3.1	-16.1	40.5	40.5	1	-142
88	-4.1	-12.2	40.5	40.5	1	-142
89	5.1	-9.8	40.5	40.5	1	-142
90	-5.1	-9.8	40.5	40.5	1	-142
91	6.1	-8.2	40.5	40.5	1	-142
92	-6.1	-8.2	40.5	40.5	1	-142
93	7.1	-7.1	40.5	40.5	1	-142
94	8.1	-6.2	40.5	40.5	1	-142
95	-0.5	0.0	40.5	40.5	1	-142
96	-1.5	0.0	40.5	40.5	1	-142
97	-2.5	0.0	40.5	40.5	1	-142
98	-3.5	0.0	40.5	40.5	1	-142
99	4.5	0.0	40.5	40.5	1	-142
100	-4.5	0.0	40.5	40.5	1	-142
101	5.5	0.0	40.5	40.5	1	-142
102	-5.5	0.0	40.5	40.5	1	-142
103	6.5	0.0	40.5	40.5	1	-142
104	7.5	0.0	40.5	40.5	1	-142
105	-7.5	0.0	31.0	31.0	3	-142
106	8.5	0.0	40.5	40.5	1	-142

107	-0.9	90.0	40.5	40.5	1	-142
108	1.3	40.9	31.0	31.0	3	-142
109	-1.3	40.9	40.5	40.5	1	-142
110	-2.2	23.4	40.5	40.5	1	-142
111	-3.1	16.1	40.5	40.5	1	-142
112	-4.1	12.2	40.5	40.5	1	-142
113	5.1	9.8	40.5	40.5	1	-142
114	-5.1	9.8	40.5	40.5	1	-142
115	6.1	8.2	40.5	40.5	1	-142
116	-6.1	8.2	40.5	40.5	1	-142
117	7.1	7.1	40.5	40.5	1	-142
118	8.1	6.2	40.5	40.5	1	-142
119	-1.8	73.9	40.5	40.5	1	-142
120	-2.3	49.1	40.5	40.5	1	-142
121	-3.0	34.7	40.5	40.5	1	-142
122	3.9	26.3	31.0	31.0	3	-142
123	-3.9	26.3	40.5	40.5	1	-142
124	-4.8	21.0	40.5	40.5	1	-142
125	5.8	17.5	40.5	40.5	1	-142
126	-5.8	17.5	40.5	40.5	1	-142
127	6.7	14.9	40.5	40.5	1	-142
128	7.7	13.0	40.5	40.5	1	-142
129	2.6	90.0	40.5	40.5	1	-142
130	-2.6	90.0	40.5	40.5	1	-142
131	-2.8	68.9	40.5	40.5	1	-142
132	-3.3	52.4	40.5	40.5	1	-142
133	-4.0	40.9	40.5	40.5	1	-142
134	-4.8	33.0	40.5	40.5	1	-142
135	-5.6	27.4	40.5	40.5	1	-142
136	7.5	20.4	40.5	40.5	1	-142
137	-7.5	20.4	31.0	31.0	3	-142
138	-3.5	81.8	40.5	40.5	1	-142
139	3.8	66.6	31.0	31.0	3	-142
140	-3.8	66.6	40.5	40.5	1	-142
141	-4.3	54.2	40.5	40.5	1	-142
142	4.9	44.7	40.5	40.5	1	-142
143	-4.9	44.7	40.5	40.5	1	-142
144	-5.7	37.6	40.5	40.5	1	-142
145	6.5	32.2	31.0	31.0	3	-142
146	-6.5	32.2	40.5	40.5	1	-142
147	8.3	24.8	40.5	40.5	1	-142
148	-4.3	90.0	40.5	40.5	1	-142
149	-4.4	77.0	40.5	40.5	1	-142
150	-4.8	65.2	40.5	40.5	1	-142
151	-5.3	55.3	40.5	40.5	1	-142
152	-5.9	47.2	40.5	40.5	1	-142
153	8.3	31.7	40.5	40.5	1	-142
154	-8.3	31.7	40.5	40.5	1	-142
155	-5.2	84.5	40.5	40.5	1	-142
156	-5.4	73.9	40.5	40.5	1	-142
157	6.3	56.0	31.0	31.0	3	-142
158	7.6	43.3	40.5	40.5	1	-142
159	-7.6	43.3	31.0	31.0	3	-142
160	8.3	38.6	40.5	40.5	1	-142
161	-6.1	90.0	40.5	40.5	1	-142

162	6.1	80.6	31.0	31.0	3	-142
163	-6.1	80.6	40.5	40.5	1	-142
164	-6.8	63.6	31.0	31.0	3	-142
165	7.9	50.4	40.5	40.5	1	-142
166	8.6	45.2	40.5	40.5	1	-142
167	-6.9	85.9	40.5	40.5	1	-142
168	-7.1	77.8	40.5	40.5	1	-142
169	7.4	70.1	40.5	40.5	1	-142
170	7.8	63.1	40.5	40.5	1	-142
171	-8.3	56.9	40.5	40.5	1	-142
172	-7.8	90.0	40.5	40.5	1	-142
173	-8.7	-86.7	40.5	40.5	1	-142
174	-7.3	-56.5	40.5	40.5	1	-142
175	-7.6	-43.3	40.5	40.5	1	-142
176	8.7	-11.5	40.5	40.5	1	-142
177	8.7	11.5	40.5	40.5	1	-142
178	-8.7	-11.5	40.5	40.5	1	-142
179	8.3	56.9	40.5	40.5	1	-142
180	8.4	68.9	40.5	40.5	1	-142

The Development and Application of a Cost per Minute Metric for the Evaluation of Mobile Satellite Systems in a Limited-Growth Voice Communications Market

by
Michael David Violet

Submitted to the Department of Aeronautics and Astronautics on August 10, 1995
in partial fulfillment of the requirements
for the Degree of Master of Science in Aeronautics and Astronautics

Abstract

Five companies have recently filed for a license with the Federal Communications Commission to provide handheld mobile communication services in the United States. Three of these companies were awarded licenses in January 1995, while Inmarsat and other non-US companies have announced their intentions to implement systems addressing the same market. The architectures proposed for each of these systems differ substantially in their selection of satellite constellations, multiple access schemes, antenna designs, service availability and network configurations. The effectiveness of each of these design approaches must be measured by how cost effectively they are able to satisfy the expected market.

A market model has been developed to estimate the addressable minutes for the first twelve years of this burgeoning market. Although optimism abounds regarding the size of the expected market, it is quite possible the market may not grow as much or as quickly as anticipated. Systems designed to operate in a large market may be poorly equipped to provide cost effective solutions in a smaller market.

A computer model has been developed to estimate the billable capacity of five mobile satellite services (MSS) designs at different levels of market penetration. To evaluate their effectiveness when operating in a limited market, the billable capacity for each system has been determined at 10% and 31% of the expected market. Life cycle costs have been estimated for each of the systems to address the market over a twelve year period. Costs evaluated include development and operations costs for satellites, launchers, gateways, insurance and PSTN connections. The effectiveness of each system has been evaluated on the basis of the cost per billable minute required to achieve an internal rate of return of 30%.

All systems are shown to provide cost effective services when adressing 31% of the expected market, but costs begin to approach current Inmarsat rates at 10% of the market. With equal market penetration, the system modeled after Globalstar, LEO-48, provides the most cost-effective service, while the LEO-66 system, modeled after Iridium, requires the highest cost per minute. These results are shown to be very dependent on the level of market penetration allowed, and indicate that other factors such as marketing strategy, quality of service and access to the global marketplace will dominate.

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Thesis Copies	$100.00		Stipend	Total	Amount	Total	Amount
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TOTAL	$357.73	1/31/95	$738.93	$2,301.71	$0.00	$0.00	$2,301.71
		2/28/95	$738.93	$3,040.64	$0.00	$0.00	$3,040.64
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		3/7/95	$0.00	$6,775.83	($124.50)	($174.98)	$6,600.85
		3/31/95	$738.93	$3,779.57	$0.00	$0.00	$3,779.57
		4/28/95	$738.93	$4,518.50	$0.00	$0.00	$4,518.50
		5/31/95	$738.93	$5,257.43	$0.00	$0.00	$5,257.43
		6/30/95	$759.20	$6,016.63	$0.00	$0.00	$6,016.63
		7/31/95	$759.20	$6,775.83	$0.00	$0.00	$6,775.83
		8/20/95	$0.00	$6,775.83	($100.00)	($357.73)	$6,418.10
		8/21/95	0	$7,535.03	($759.21)	($1,116.94)	$6,418.09
		8/31/95	$759.20	$7,535.03	$0.00	($357.73)	$7,177.30

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